Cognitive Interventions and Aging

The Neural Correlates of an Expanded Functional Field of View

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The size of the functional field of view (FFOV) predicts driving safety in older adults (Owsley et al., 1998), and practice-related changes in the FFOV may transfer to driving safety (Roenker, Cissell, Ball, Wadley, & Edwards, 2003). We used functional magnetic resonance imaging (fMRI) and behavioral measures to examine how practice with the FFOV task changes older adults' attentional function. Behavioral data collected outside of the MRI revealed that participants in the training group showed larger improvements across conditions than did those in the control group. fMRI data revealed training-related changes in activation in a number of brain regions. In the right precentral gyrus and right inferior frontal gyrus, increases in activation between fMRI sessions correlated positively with increases in accuracy between behavioral sessions. Practice with the FFOV task improves older adults' attentional function by increasing their recruitment of regions traditionally associated with orienting visual attention.

THE functional field of view (FFOV) task measures the spatial area in which a stimulus may receive attention. The FFOV describes the maximum distance a stimulus can be removed from the focus of attention and still be reliably detected, identified, or localized (Mackworth, 1965). The FFOV varies with both cognitive demand and developmental changes. Although an individual's FFOV may be quite large during the performance of a simple target detection task, it may grow smaller with the addition of a second task (Williams, 1989; but see R. Sekuler & Ball, 1986, for an exception) or distracting nontargets to the display (Ikeda & Takeuchi, 1975; Mackworth, 1965). Early investigators recognized that the FFOV varied in size not only "between different kinds of tasks" but also "between different kinds of people" (Mackworth, 1976, p. 318). Young children (aged 5–8), for example, are less accurate at judging peripheral stimuli than are college-aged adults (Holmes, Cohen, Haith, & Morrison, 1977). Older adults are generally slower and less accurate at peripheral stimulus judgments than are younger adults, but this effect does not interact with the retinal location of the peripheral stimuli (Scialfa, Kline, & Lyman, 1987; Sekular, Bennett, & Mamelak, 2000; Sekuler & Ball, 1986). Both cognitive demand and developmental status, then, may affect the efficiency with which an individual can extract information from the visual field.

The developmental changes measured by the FFOV have a practical relationship to a real world skill: driving. It is well established that FFOV performance predicts driving proficiency among older adults (Owsley et al., 1998). FFOV performance is more highly correlated with state-reported crash incidence than is visual health, visual function, or mental status (Owsley et al., 1991). Furthermore, both increases and decreases in the FFOV predict changes in driving safety. Owsley and colleagues (1998) reported that older adults with a 40% or greater reduction in the FFOV were twice as likely to be involved in an accident over the course of the next 3 years than were their relatively unimpaired

counterparts. Both young and old adults show improved FFOV performance as a result of practice; these effects emerge after only a few practice sessions and may endure for up to 2 years (Ball et al., 1988; Ball et al., 2002). These practice-related improvements may transfer to driving performance (Roenker, Cissell, Ball, Wadley, & Edwards, 2003).

The FFOV task provides different processing stages at which practice may improve task performance. Practice may affect processes of perceptual discrimination, improving the ability of the visual and attention systems to act on information throughout the visual field (e.g., Ho & Scialfa, 2002; Salthouse & Somberg, 1982). Indeed, some researchers claim that the FFOV task measures and trains speed of perceptual processing (e.g., Roenker et al., 2003), and both older and younger adults appear to improve visual item identification and localization across eccentricities with FFOV practice (Ball et al., 1988). Despite the traditional view of the FFOV task as a measure of perceptual processing, however, its classical implementation involves some manipulation of task demand (Mackworth, 1965; Scialfa et al., 1987; Sekuler, Bennett, & Mamelak, 2000; Sekuler & Ball, 1986). This leaves open the possibility that FFOV practice improves cognitive functions beyond perceptual processing. Previous data from our laboratory and others suggest that older adults in particular are benefited by training in dual-task paradigms (Kramer, Larish, Weber, & Bardell, 1999; Salthouse & Somberg, 1982). Because traditional measures of the FFOV often include a dual-task condition (e.g., Ball et al., 1988), it is possible that practice with the FFOV paradigm has a particular effect on older adults' ability to coordinate and control the performance of multiple tasks. Such improvements may actually precede those that occur in perceptual processing, because older adults' limited abilities to cope with dual-task conditions may prevent them from directing attention to, and learning about, individual perceptual tasks (Kramer et al., 1999).

Recent investigations of interventions that reduce age-related cognitive decline have addressed not only what psychological processes are improved, but also what changes occur in the neural structures that underlie task performance. These interventions have usually focused on reducing age-related decline in the executive functions. These functions include response inhibition, working memory, and multiple-task performance (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000), and appear to be especially vulnerable to age-related decline (West, 1996). Interventions that improve these functions in older adults typically alter prefrontal function. For example, Colcombe and colleagues (2004) found that aerobic fitness interventions that improve older adults' inhibitory control also decrease anterior cingulate and dorsal-lateral prefrontal activation; these regions are believed to mediate response selection in young adults (Banich et al., 2000; Milham et al., 2001). Erickson and colleagues (2006) reported that training in a dual-task paradigm increased reliance on left ventro-lateral prefrontal cortex, possibly reflecting a shift to a verbally mediating working memory strategy. Furthermore, these changes correlated significantly with improved dual-task performance. Strategy-related improvements in working memory drive an increase in recruitment of left ventrolateral prefrontal cortex in older adults (Logan, Sanders, Snyder, Morris, & Buckner, 2002).

In the present study, we used behavioral measures to determine the locus of practice effects on FFOV task performance. Although previous behavioral work, with both the FFOV task (Ball et al., 1988) and other visual attention paradigms (Ho & Scialfa, 2002; Salthouse & Somberg, 1982), suggests that practice may improve older adults' perceptual and visual attentional function, other behavioral (Kramer et al., 1999) and neuroimaging work (Erickson et al., 2006) suggests that practice may also affect older adults' abilities to coordinate and control the performance of multiple tasks. If we find that practice affects all conditions of our FFOV task equally, we would conclude that it primarily benefits processes of visual attention and perception. If we find that practice has a larger effect on dual-task conditions, we would conclude that it has a specific effect on older adults' ability to coordinate and control the performance of multiple tasks.

We then used this behavioral data to inform the contrasts to which we subjected our functional magnetic resonance imaging (fMRI) data. Effects of practice that behaviorally affect processes of visual attention should emerge across task conditions in the brain activation data, whereas dual-task specific behavioral effects of practice should emerge specifically in the dual-task-related brain activation data. Furthermore, we might expect to see that the general effects of practice on perceptual processes and attentional control vary in anatomical locus; in young adults, practice effects in perceptual function are usually found in visual cortex, whereas practice effects in attentional function are usually found in prefrontal and parietal regions (for a review, see Kelly & Garavan, 2005).

METHODS

Participants

We tested 45 older adults (aged 55–85). Participants had normal or corrected-to-normal vision and were right handed. We did not admit participants into the study unless they scored a minimum of 51 points on the Modified Mini-Mental State Exam (3MS; McDowell, Kristjansson, Hill, & Hebert, 1977). Mean 3MS score was 54 points. We rejected 2 participants on the basis of low 3MS scores.

We randomly assigned participants to practice ($n = 25$) and control ($n = 20$) groups. Greater attrition rates for the control group than the practice group left the two groups with unequal sample sizes. Everyone participated in a behavioral pretesting session after the fMRI pretesting session and a behavioral posttesting session prior to the fMRI posttesting session. Participants in the practice group also received an additional five behavioral practice sessions. The average number of days between initial and final fMRI sessions for the control group was 38. The average number of days between initial and final fMRI sessions for the practice group was 45.

We appreciate that higher attrition rates from the control group than the practice group may leave the reader with some doubts regarding the similarity of our samples. Of particular concern is that greater attrition rates among controls may reflect differences in the treatment of the two samples. For example, practice participants might have been more motivated to complete the study because they had more frequent contact with the experimenters. To address these issues, we report the cause of attrition for each of our participants. We assigned participants to practice or control groups before their initial fMRI screening, before we were aware of their tendency towards claustrophobia or their ability to fit in the very small bore of our head-only MRI. Participants who were unable to complete MRI testing went on to complete behavioral testing and training because these measures were of interest for other projects in the lab. Consequently, we did not replace participants who were unable to tolerate MRI testing in our sample. In the practice group, 7 participants did not complete their MRI sessions. Three participants were unable to continue due to claustrophobia, and 1 was unable to fit in the bore of the magnet. Two training participants also left the study due to the death of a spouse and to heart surgery. We removed 1 practice participant from our sample after that person failed to complete the practice sessions within 16 weeks. In the control group, 10 participants were unable to complete fMRI scanning. Three participants were unable to continue due to claustrophobia, and 2 were unable to fit inside the bore of the MRI. Two control participants produced unusable fMRI data during pretesting, 1 due to a large biological artifact and the other due to MRI technologist error. Three control participants also left the study due to spontaneous vacation plans, fear of repeated exposure to magnetic fields, and irritation at being unable to find the MRI facility, respectively. Events that occurred during the first fMRI testing session, then, seemed to entirely account for the higher incidence of attrition in controls. At this point, of course, participants in the practice and control groups had received exactly the same treatment, so differences in treatment could not account for the higher rates of attrition.

Testing Sessions

Each individual participated in neuroimaging and behavioral pretest and posttest sessions. Neuroimaging pretesting preceded behavioral pretesting sessions, and neuroimaging posttesting sessions followed behavioral posttesting sessions. Each

neuroimaging session lasted approximately 100 minutes, whereas each behavioral session lasted approximately 90 minutes. Individuals assigned to the practice group participated in an additional five behavioral practice sessions; each practice session lasted approximately 45 minutes.

Behavioral Stimuli and Design

Participants performed five blocks of trials in each testing session. Stimulation was constant across blocks (see Figure 1). Each trial began with a 400 ms fixation cross, followed by a 400 ms cue display. This display contained four boxes evenly spaced around the center of the screen; the outermost edge of each box was placed 5.67° of visual angle from fixation. Next, a *T* appeared in one of the four boxes, and a + appeared in each of the remaining boxes. These stimuli subtended 2.52° of visual angle horizontally and vertically. Eighteen tilted lines appeared coincident with the *T*. One line tilted to the left, and the remaining 17 tilted to the right. These lines were evenly distributed in the periphery; 6 formed a circle with a radius of 13.87°, and the remaining 12 formed a circle with a radius of 27.74°. Both circles were centered at fixation. Display duration was 160, 213, and 266 ms. A 250 ms mask display followed target presentation. Rectangular figure eights replaced the center items, and asterisks replaced the tilted lines. Following the mask display, one (single-task condition) or two (dual-task condition) displays prompted participants to use the mouse to indicate the location of the target item or items. Participants received points for each correct localization and were apprised of their performance and point total at the end of each trial. Participants began a new trial by clicking the mouse on the fixation cross.

Central task.—During the first and fifth blocks, participants responded to the location of the *T*. Participants received 4 practice trials and 36 test trials in each block, for a total of 72 test trials. The target stimulus was equally likely to appear in each of the four boxes that surrounded fixation. The four boxes remained on the screen through the mask and response displays. Participants indicated the location of the *T* during the response display by using the mouse to click on the box it had occupied.

Peripheral task.—During the second and fourth blocks, participants responded to the location of the left tilted line. Participants received 4 practice trials and 72 test trials in each block, for a total of 144 test trials. The target stimulus was equally likely to appear in any 1 of 12 possible locations (these locations included the six items that comprised the inner circle and the six items in the outer circle that occupied the same radial positions as those in the inner circle). During the response period, empty circles occupied the locations of the tilted lines. Participants indicated the radial location of the left tilted line by using the mouse to click on any circle that occupied the same radial position as the target.

Dual task.—During the third block, participants located both the *T* and the tilted line. Participants received 4 practice trials and 144 test trials. After each trial, we prompted participants to respond first to the center item and then to the peripheral item.
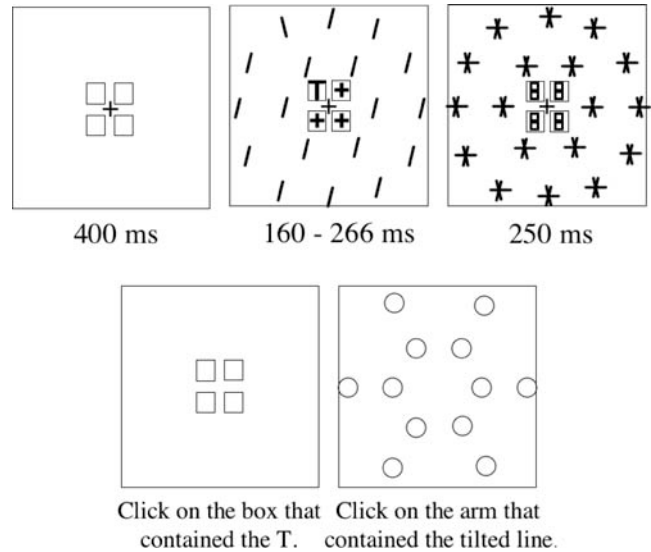

Figure 1. Displays used during behavioral testing and practice sessions.

Behavioral Practice Procedures

Practice sessions were identical to the behavioral testing session, except that participants received 70 test trials during both single-task conditions and 210 test trials in the dual-task condition in each of the practice sessions. Participants received feedback in the practice blocks as well as in the testing blocks.

Neuroimaging Stimuli and Design

We used a slow event-related design to assess brain activation during FFOV task performance. Participants performed three task conditions: a central task condition (in which participants located a *T*), a peripheral task condition (in which participants located a tilted line presented among vertical lines), and a dual-task condition (in which participants located the targets simultaneously; see Figure 2). Because instructions, not visual stimulation, determined task condition, task conditions were blocked.

Although we attempted to make our behavioral training version of the FFOV tasks similar to others reported in the literature, we varied the version of the task used in the MRI environment from that used for behavioral training for a number of reasons. First, using a mouse or keyboard in the MRI environment is not possible; instead we were restricted to a four-button response pad. Second, the vertical range of the goggles used to present stimuli in the MRI is somewhat limited; we therefore had to limit our display to the horizontal meridian. Third, the MRI environment is somewhat unsettling to older adults, so we wished to keep stimulus display conditions and instructions as simple as possible. To this end, we omitted any feedback and changed task requirements as infrequently as possible. Furthermore, feedback in the MRI environment would have produced changes in neural regions active in interpreting that feedback, something we wished to avoid. Finally, although accuracy usually determines the size of the FFOV, incorrect trials produce unusable fMRI data. In order to obtain an adequate number of trials from participants in a reasonable
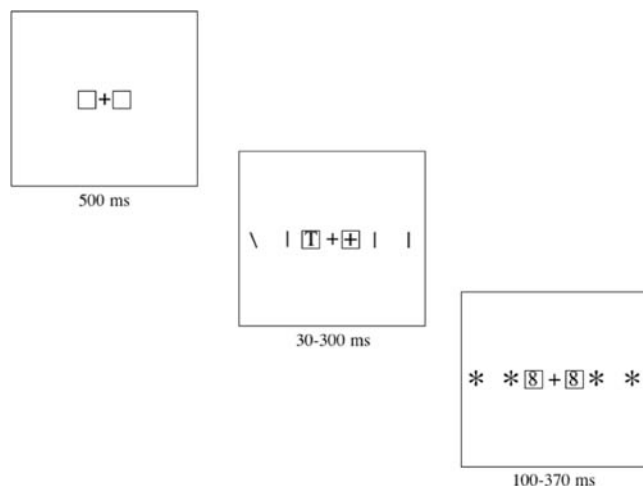
Figure 2. Preparation screen, stimulus screen, and mask screen viewed by participants in the neuroimaging version of the functional field of view task.

amount of testing time, we made the neuroimaging task easier than that used during behavioral testing and training by reducing the number of potential target locations for both tasks.

Visual stimulation was constant across task conditions. In each trial, participants viewed a fixation cross for 1 s. Two boxes, which served to cue the participants that the trial was about to begin, appeared next, each centered 1.4° of visual angle from fixation. These boxes subtended 2.3° of visual angle vertically and horizontally. These remained empty for 500 ms, after which a *T* appeared in one of the two boxes, while a + appeared in the other. These items subtended 2° of visual angle vertically and horizontally. At the same time, four lines subtending 2° of visual angle appeared in peripheral locations. Each line was centered on the horizontal meridian; two appeared 7.4° of visual angle to the right and left of fixation. The other two appeared 14.4° of visual angle to the right and left of fixation. Three of these lines were vertical, but in 80% of the displays one of the lines tilted 45° to the left. Masks followed the task-relevant stimuli, and remained for the amount of time necessary to make the total stimulus-mask duration 400 ms. An 8,100 ms ISI followed this mask, making each trial 10 s in length. Participants responded using a four-button response pad.

All participants received 40 practice trials in each condition during pretesting. An adaptive algorithm (parametric estimation by sequential testing) controlled stimulus exposure duration, allowing us to determine the exposure duration at which the participant could perform trials in task block with 85% accuracy (Pollack, 1971). We note that titrating exposure duration was possible only for each block (center, peripheral, dual); titrating for proximal and distal line positions would have made the exposure of the stimuli predictive of the line location. These stimulus durations remained constant between pretesting and posttesting in order to ensure that training-related differences did not simply reflect differences in the exposure duration of task-relevant stimuli. Stimulus durations were no briefer than 34 ms (to ensure that participants explicitly recognized items) and were no longer than 316 ms (to ensure that participants made a single fixation).

Central task.—During the first block of 60 trials, participants indicated whether the *T* appeared in the right or left center box by pushing a key on the response pad with their right or left index finger. The location of the *T* varied equiprobably between the right and left box on any given trial. Tilted lines, to which participants did not respond, occupied each of the four positions 12 times. Average exposure duration for this task was 247 ms; exposure durations ranged from 50 ms to 316 ms. All presentation conditions were fully counterbalanced. The duration of this task was about 8 minutes.

Peripheral task.—During the second block of 80 trials, participants indicated whether the leftward tilting line appeared on the right or left side of the screen by pressing a key with their right or left middle finger. This line occupied each of the four positions 16 times. We included the remaining trials to prevent participants from basing their decision about the line's location on information from only one side of the visual field. Participants withheld responses to trials that did not contain tilted lines. The centrally presented *T*s, to which participants did not respond, appeared with equal likelihood in the two boxes on each trial. All presentation conditions were fully counterbalanced. Average exposure duration for this block was 297 ms; exposure durations ranged from 166 ms to 316 ms. The duration of this task was about 12 minutes.

Dual task.—During the third block of 120 trials, participants performed both the central and the peripheral tasks. We instructed participants to respond first to the central task, using their right or left index finger, and then to the peripheral task, using their right or left middle finger. In this block of trials, the *T* was equally likely to occur in either box on each trial. The tilted line occupied each of the four positions 24 times. Participants responded only to the center *T* on the trials that contained no tilted lines. The order of all presentation conditions was fully counterbalanced. All participants required the maximum exposure duration of 316 ms to perform this task. The duration of this task was about 23 minutes.

Neuroimaging Procedures

Participants were tested in a 3-Tesla Siemens Allegra Scanner (Siemens Medical Solutions Inc., Malvern, PA) equipped for echo planar imaging. Stimuli appeared through goggles designed by Magnetic Resonance Technologies (Northridge, CA). We acquired a total of 1,397 T2*-weighted echo planar images for each participant (repetition time = 2,000 ms; echo time = 26 ms; flip angle = 60°). We thus acquired a three-dimensional echo planar image volume every 2 seconds; the peak echo from each pulse occurred 26 seconds after pulse onset. Each echo planar image consisted of 16 contiguous slices (3.75 × 3.75 × 7.0 mm) parallel to the anterior commissure–posterior commissure line. We also collected a high-resolution (FOV = 256 × 256) T1-weighted magnetization prepared rapid gradient echo image (repetition time = 2100 ms; echo time = 4.38 ms; flip angle = 8°) of 128 contiguous slices (1.3 mm thick) to assist in registering our echo planar images to standard space.

RESULTS

We calculated each participant's accuracy for locating distally positioned peripheral target items during the fMRI

pretesting session. We rejected any participant who did not produce at least 16 correct trials in the distal-dual condition of the first scanning sessions (33% accuracy). Because we required correct responses to both center and peripheral stimuli and because there were three possible responses to peripheral stimuli (left, right, and absent), chance performance in the dual-task condition was 16.5%. Smaller numbers of trials were inadequate to support analysis. Using these criteria, we rejected 17 participants. We found no differences in performance in our battery of neuropsychological tasks between participants whom we included and those whom we did not, suggesting that our results may be generalizable across participants. We report these data in the Appendix. Analysis of participants' performance during the initial behavioral testing session confirmed that differences in these participants' abilities to perform the FFOV task persisted outside of the scanning environment.

We then analyzed the demographic data for the practice ($n = 18$) and control ($n = 10$) participants. We found no significant differences between the two groups in any of the demographic data (see Table 1).

Behavioral Analysis

We report the behavioral practice effects for those participants whose fMRI data we included in the present study. We calculated the average accuracy in each condition at pretest and posttest for 24 participants (we lost data from 4 participants due to computer user error). We subjected these data to a mixed-mode analysis of variance, using the between-groups factor of training group (practice, control) and the within-subjects factors of session (pretest, posttest), exposure time (160 ms, 213 ms, 266 ms), dual-task condition (single task, dual task), task (central, peripheral), and line position (proximal, distal). In deference to space limitations, we report only those results that reflected a significant effect of testing time.

We found a main effect of session, $F(1, 22) = 53.56$, $p < .00001$, and a significant interaction between session and exposure time, $F(2, 44) = 5.7$, $p < .01$. We also found a significant interaction among session, exposure time, and task conditions, $F(2, 44) = 4.07$, $p < .05$. A significant four-way interaction among session, exposure time, dual-task condition, and task, $F(2, 44) = 3.75$, $p < .05$, which we present in Figure 3, qualified these effects. Of special interest is the fact that when exposure duration was 160 ms or 213 ms, performance improved across all conditions equally. When exposure duration was 266 ms, performance improved most for peripheral targets under dual-task conditions. Note that pretest single-task performance was quite good with exposure durations of 266 ms (> 80%), suggesting either that such conditions enable rapid dual-task improvements to occur (with fewer than than two sessions of practice) or that there is a ceiling on the performance gains that individuals may achieve when pretest performance of single tasks is already very good.

When we looked for specific practice effects, we found a significant interaction between testing group and session, $F(1, 22) = 17.2$, $p < .001$. Neuman–Keuls pairwise comparisons revealed that participants in the practice (62%) and control (62%) groups showed equivalent accuracy at pretest ($p > .88$). At posttest, however, participants in the practice group (76%) showed significantly higher ($p < .001$) accuracy than did participants in the control group (66%). No interaction between

Table 1. Demographic Data for Practice and Control Participants

Measure	Practice		Control	
	M	SD	M	SD
Age (y)	66.28	7.72	67.60	5.46
Education (y)	15.86	3.34	16.00	3.86
Modified Mini-Mental State Exam	55.72	1.32	54.10	2.18
Digit Span				
Forward	8.33	2.47	7.30	3.06
Backward	7.39	2.59	5.70	1.16
Kaufman Brief Intelligence Test				
Composite	114.94	12.58	116.20	7.27
Verbal	112.44	15.86	113.60	9.13
Matrices	112.50	15.06	115.40	6.65
Perceptual skills				
Box completion	40.72	14.00	39.00	8.74
Digit copying	65.89	13.83	66.10	8.25
Digit symbol translation	35.22	7.24	34.30	7.50
Sequential complexity	38.56	6.52	36.50	9.48
Computation span	3.00	1.19	2.60	0.70
Trail-making task				
Trails A	36.56	11.80	39.50	10.44
Trails B	73.50	27.29	73.00	35.53
Letter comparison				
Three items	16.22	2.39	15.40	4.17
Six items	8.11	2.05	7.90	4.17
Nine items	5.83	1.29	5.90	2.02
Stroop				
Reading	96.56	5.39	89.80	12.16
Color naming	73.28	8.65	66.20	19.21
Interference	37.39	8.37	34.70	10.90
Stroop effect*	0.37	0.09	0.35	0.11

Notes: M = mean; SD = standard deviation.

*The Stroop effect was calculated by subtracting the number of color words in colored ink read from the number of ink colors named and dividing this by the number of color words in black ink read.

testing session and any other factors met or approached conventional levels of significance ($p > .10$). Specifically, we note that the factors testing session, exposure duration, dual-task condition, and task did not interact with testing group; we did not, therefore, find any evidence that more extended practice with the FFOV task had a specific effect on dual-task processes.

fMRI Behavioral Analysis

We calculated each participant's average accuracy to target items under single-task and dual-task conditions during performance of the fMRI task. We subjected these data to a mixed-mode analysis of variance using training group (practice, control) as a between-subjects factor and session (pretesting, posttesting), dual-task condition (single, dual), task (center, peripheral), and peripheral target location (proximal, distal) as within-subjects factors.

We found a significant main effect of session, $F(1, 26) = 6.35$, $p < .02$, and an interaction between session and dual-task condition, $F(1, 26) = 5.60$, $p < .05$. We also found a significant interaction among session, dual-task condition, and task conditions, $F(1, 26) = 13.96$, $p < .0001$. Neumann–Keuls pairwise comparisons revealed that performance improved
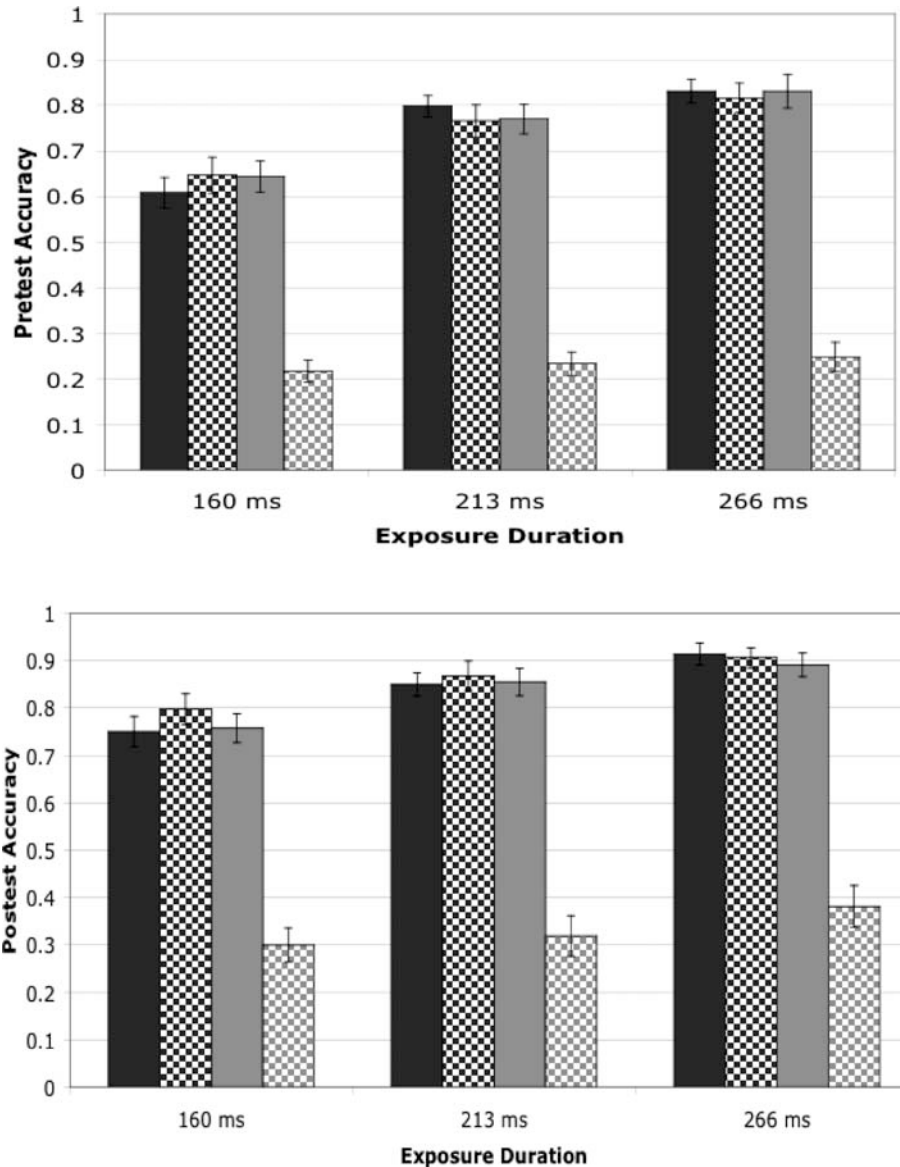
Figure 3. Interaction among the factors session, exposure duration, dual-task condition, and task in behavioral data collected outside of magnetic resonance imaging. The upper graph shows accuracy at pretest and the lower graph shows accuracy at posttest. For exposure durations of 266 ms, both single-task conditions and the dual-task center conditions showed a greater decrease in improvement than at other exposure duractions. The peripheral dual-task condition showed a slight increase in dual-task improvement at 266 ms.

significantly only for peripheral task performance under dual-task conditions (pretest = 69%, posttest = 80%, $p < .0001$; see Figure 4). No other conditions improved significantly between pretest and posttest ($p > .80$). We note that our failure to find pretest/posttest differences in these other conditions may reflect a ceiling effect. Our manipulation of exposure duration to produce relatively good performance during pretest may have limited our ability to detect changes in performance at posttest.

fMRI Analysis

We performed several image preprocessing steps to prepare the neuroimaging data for analysis. We discarded the first six echo planar images from each block to be certain that data included in the analysis only reflected steady-state scanner activity. We motion-corrected data by using McFLIRT (FSL 3.1, fMRIB Analysis Group, Oxford, United Kingdom; Jenkinson, Bannister, Brady, & Smith, 2002; Smith et al., 2004) and spatially smoothed the data using a three-dimensional Gaussian kernel (half-width, half-maximum = 3 mm). We applied lowpass (half-width, half-maximum = 1 s) and highpass (half-width, half-maximum = 30 s) temporal filters using ip (FSL 3.1; Bannister, Flitney, Woolrich, & Smith, 2000; Smith et al., 2004).

We used FEAT version 5.2 (fMRI Expert Analysis Tool, FSL 3.2; fMRIB Analysis Group, Oxford, United Kingdom; Smith et al., 2004; Woolrich, Ripley, Brady, & Smith, 2001) to submit functional data to multiple regression analysis. We constructed our regressors of interest using the onset time of
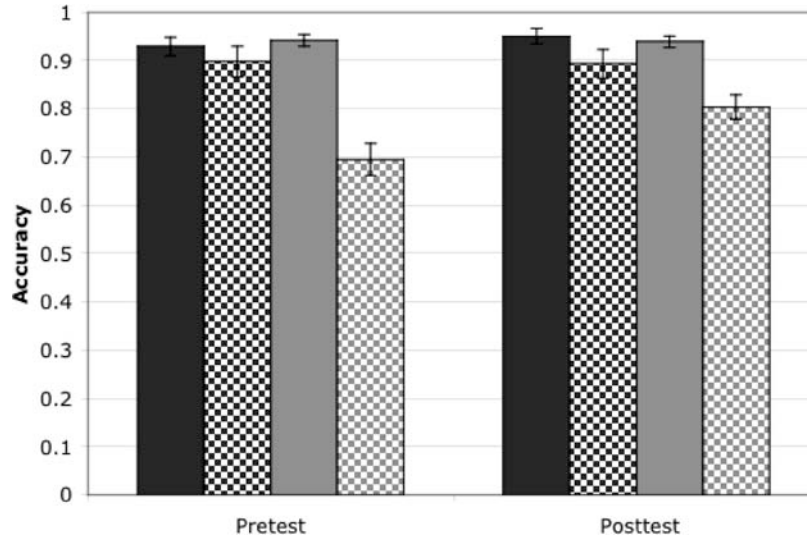
Figure 4. Interactions between the factors session, dual-task condition, and task condition in behavioral data collected during magnetic resonance imaging. Performance improvements were greatest on the peripheral trials performed under dual-task conditions.

each event type convolved with the canonical hemodynamic response (Friston et al., 1997). We modeled error trials and head motion as regressors of no interest. This analysis yielded contrast parameter estimates for center-task proximal trials, center-task distal trials, peripheral-task proximal trials, peripheral-task distal trials, dual-task proximal trials, and dual-task distal trials for each participant.

Treating intraparticipant variability as error, we used FEAT's ordinary least squares mixed-effects analysis to identify those regions in which pretest/posttest differences in activity differed between participants in the training and control groups. We passed lower level contrast parameter estimates from each voxel in each participant in each condition for each session to a single higher level analysis. The activation changes we report reflect differences in the ability of the predicted BOLD response at each voxel for each condition to fit the data acquired during pretesting and posttesting sessions. To be certain that training-related changes did not reflect decreases in task-related deactivations, we limit the results we report to regions that showed positive $(Z > 0)$ task-related activity across individuals and task conditions at pretest.

Because the behavioral data we collected outside of the MRI indicated that practice-specific improvements generalized across task condition, we report that those regions showed an interaction between testing session and practice group $(Z > 4.0,$ cluster $p < .05$; see Table 2). Clusters in the precentral gyrus bilaterally, the right superior parietal lobule, the right inferior parietal lobule, the medial superior frontal gyrus, the medial precuneus, the right inferior frontal gyrus, the right middle temporal gyrus, the left medial frontal gyrus, and the left postcentral gyrus showed a greater increase at posttest for practice participants than for control participants (see Figure 5). Clusters in the thalamus and right lingual gyrus showed a greater decrease at posttest for practice participants than for control participants.

We did not find an interaction between practice group and session for performance in the fMRI version of the FFOV task. This may reflect both decreased anxiety during fMRI scanning

and the benefits of practice in the two behavioral testing sessions for the control participants. We hasten to point out, however, that failure to find an interaction between practice group and session does not imperil our conclusion that practice caused changes in neural activation. In fact, some researchers

Table 2. Clusters Showing a Significant Interaction Between Testing Group and Training Session

Lobe	Region	BA	X	Y	Z	Peak Z	K	r
Frontal	Precentral gyrus (L)	6	−57	−6	38	5.96	93	0.13
	Precentral gyrus (R)	4	55	−15	42	5.07	45	0.34
	Precentral gyrus (R)	6	40	−9	63	5.04	42	0.43*
	Precentral gyrus (R)	6	44	−8	42	5.56	40	0.55*
	Medial frontal gyrus (L)	6	−15	−3	53	4.87	26	0.03
	Inferior frontal gyrus (R)	44	38	7	22	5.11	26	0.29
	Superior frontal gyrus (R)	10	−2	60	−5	5.30	25	0.12
Occipital	Middle temporal gyrus (R)	39	50	−77	9	4.88	32	−0.03
	Lingual gyrus (R)	17	16	−88	−4	−5.08	36	−0.33
Parietal	Superior parietal lobule (R)	7	31	−54	51	5.70	131	0.23
	Postcentral gyrus (R)	40	37	−34	47	5.59	71	0.30
	Precuneus	19	13	−85	38	5.18	69	−0.004
	Inferior parietal lobule (L)	2	−35	−32	44	4.77	27	0.17
Thalamus	Ventral posterior medial (L)	—	−14	−22	0	−5.77	125	−0.17

Notes: L = left hemisphere; R = right hemisphere; BA = Broadman's area; X, Y and Z = Talaraich coordinates of maximum z score; Z = maximum z score; K= number of voxels; r = correlation coefficient between behavioral and neural changes.

Clusters showing a significant interaction between session and training group (Z > 4.0; cluster p < .05) and the correlation of these changes with individual changes in behavioral measures collected outside of the scanner. Positive Zs reflect greater signal increase from pretest to posttest in trained participants. Negative Zs reflect greater signal decrease from pretest to posttest in trained participants.
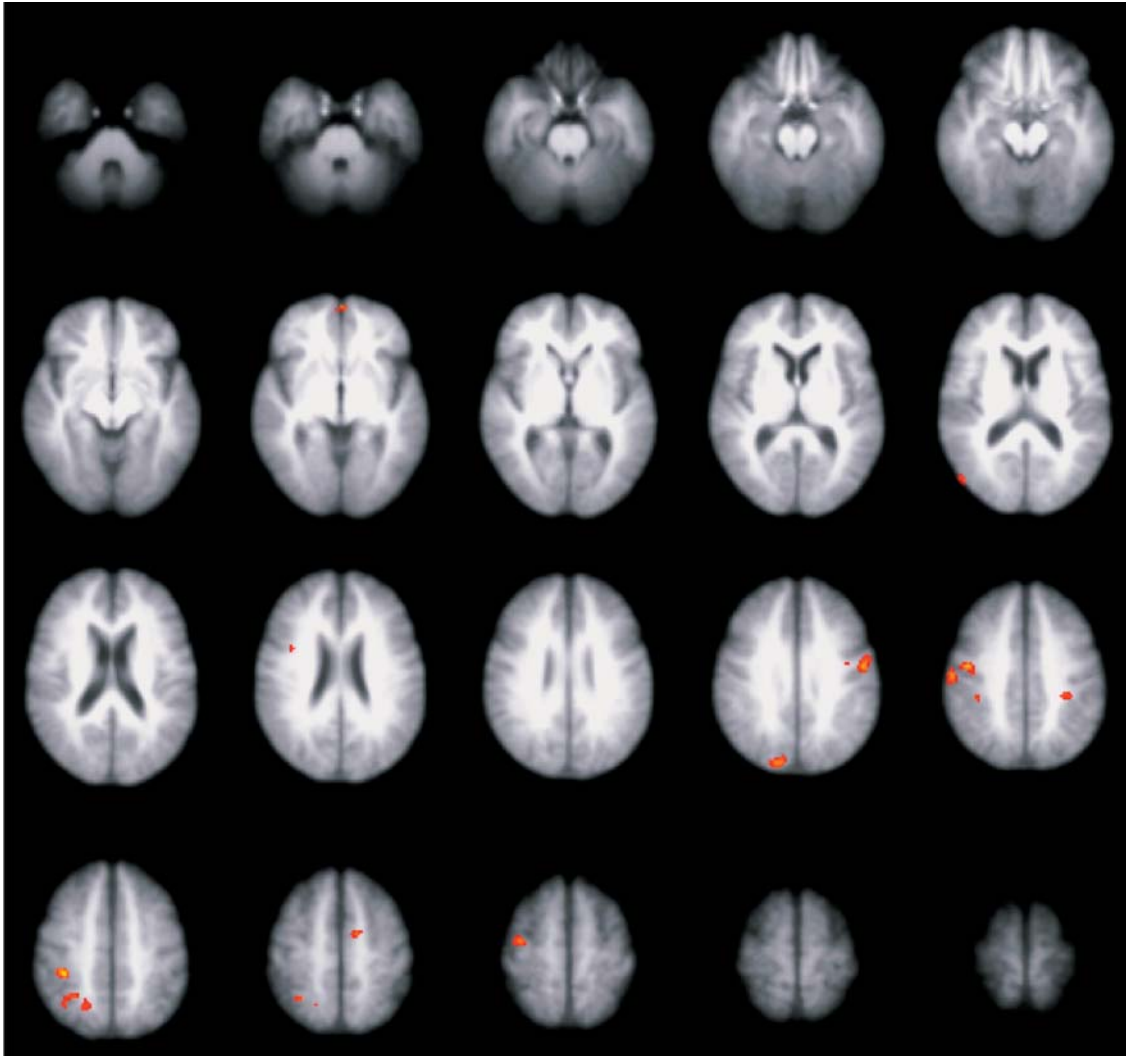
*p < .05.

Figure 5. Regions in which practiced participants showed greater increases between pretesting and posttesting session than did control participants ($Z > 4.0$; k < 2.5; $p < .05$).

have proposed that practice-related differences in behavioral performance during neuroimaging actually confound in the interpretation of the neuroimaging data (for a review of this issue, see Poldrack, 2000).
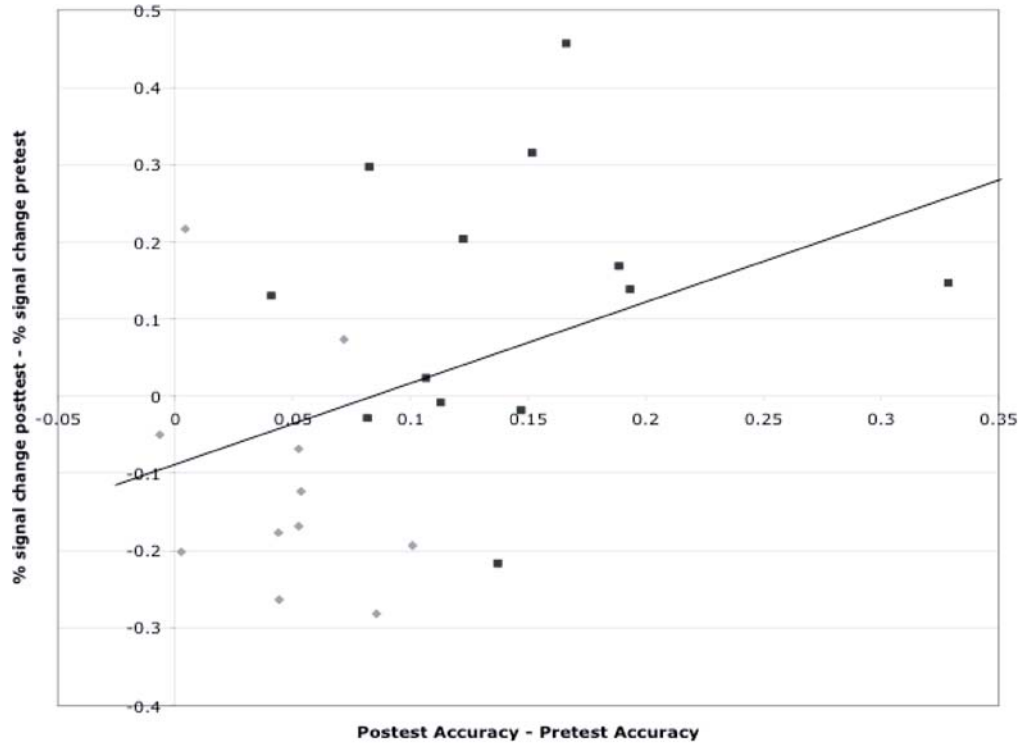
We used correlational analysis to examine the relationship between performance in the behavioral testing sessions, which were sensitive to practice effects, and the brain regions that showed an interaction between practice group and session. To do this, we calculated the average change in performance between behavioral pretesting and posttesting sessions for each individual. We then used featquery (FSL 3.2, FMRIB Analysis Group, Oxford, U.K.; Smith et al., 2004) to extract the average percent signal change for each individual in each condition for each of the clusters identified previously. For each cluster, we subjected each individual's average difference in behavioral performance and average difference in percent signal change to regression analysis. We found significant correlations in improvements in accuracy and increases in brain activation in right inferior frontal gyrus ($r = .405$, $t(22) = 2.07$, $p < .05$, see Figure 6) and the right ventral precentral gyrus ($r = .508$,

$t(22) = 2.76$, $p < .05$, see Figure 7). In no other regions did the correlation between change in behavioral performance and change in brain activation approach conventional levels of significance ($p > .10$).

DISCUSSION

Although a plethora of data indicates that older adults' ability to coordinate and control the performance of multiple tasks is especially sensitive to training, we found no specific evidence that changes in these skills underlie practice-related improvements in performance of the FFOV task. Similar to other researchers (Ball et al., 1988), we found that practice in the FFOV task improved older adults' performance across task conditions. The behavioral pretesting and posttesting revealed that participants in the practice group made greater performance gains in all conditions than did control participants. We did find evidence that all participants showed somewhat larger improvements in performance of the peripheral target task under dual-task conditions in the behavioral data collected both inside and
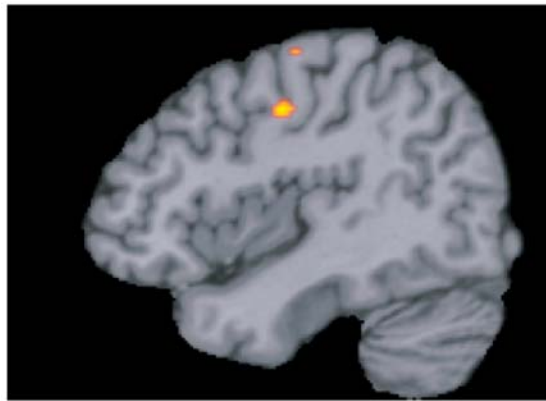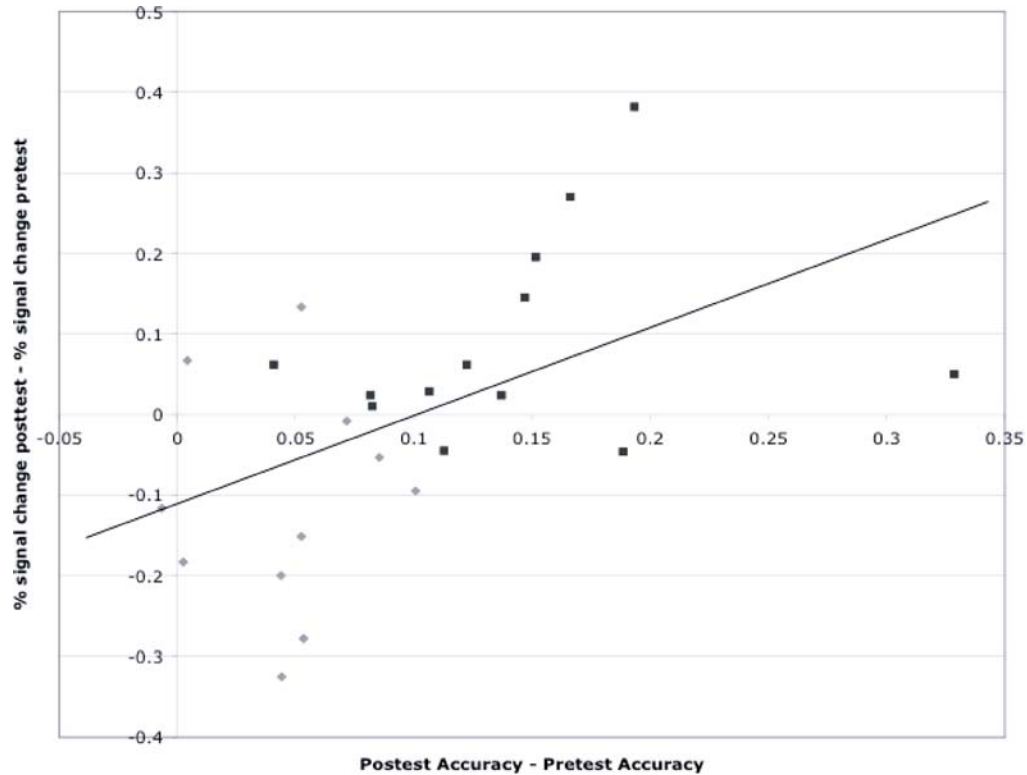
Figure 6. Positive correlation between behavioral improvements measured outside of magnetic resonance imaging and change in signal in right inferior frontal gyrus.

outside of the MRI system. These effects may reflect either a ceiling on the performance gains that could be achieved for the other three conditions or performances gains that occur with a very small amount of practice. More extensive practice, however, appears to have its most reliable effect on processes of visual attention and perception used across task conditions. These data are consistent with those collected from young adults performing a paradigm similar to ours; Ahissar, Laiwand, and Hochstein (2001) reported that practice-related improvements on individual single tasks could entirely account for practice-related improvements in the simultaneous search for two visual items (one centrally located, one peripherally

located). Our data indicate that the same is likely true for older adults.

The neuroimaging results allow us to draw more specific conclusions regarding how practice improves older adults' performance in the FFOV task. Because our behavioral data indicate that the most reliable effects of multiple practice sessions were equally present in single- and dual-task conditions, we combined the imaging data from these conditions. We found a significant effect of practice on regions in the right inferior frontal gyrus and right precentral gyrus. Participants in the practice group increased activation in these regions to a greater extent than did participants in the control group.

X=44

Figure 7. Positive correlation between behavioral improvements measured outside of magnetic resonance imaging and change in signal in precentral gyrus.

Furthermore, individuals' activation increases in these regions correlated significantly with their improvements in task performance measured outside of the scanner. Shifting and reorienting the focus of attention often produces activation in these regions (for a review, see Corbetta & Shulman, 2002). The midlateral region of the precentral gyrus are believed to be the human homologues of the frontal eye fields, which are long thought to mediate covert attentional shifting (e.g., Nobre et al., 1997). More recent research has indicated that the frontal eye fields are important in both providing top-down control over visual search mechanisms (maintaining target defining features during search; Corbetta & Shulman, 2002; Grosbras, Laird, &

Paus, 2005; Serences & Yantis, 2006), and in shifting attention to targets when they appear (Serences et al., 2005; Serences & Yantis, 2006). In this way, FEF plays a role in both top-down and stimulus-driven attentional control. The practice-related changes we observed in FEF may be related to either or both of these functions. The inferior frontal gyrus may behave more like a circuit breaker, in that it signals a need to reorient attention when a target occurs outside of the current focus of attention (Arrington, Carr, Mayer, & Rao, 2000; Corbetta & Shulman, 2002; Weissman, Roberts, Visscher, & Woldorff, 2006). Both regions respond when distractors share a defining feature with the target (de Fockert, Rees, Frith, & Lavie, 2004;

Serences et al., 2005; Serences & Yantis, 2006), indicating that activation in FEF and inferior frontal gyrus reflects either the capturing of attention by a stimulus that either partially or completely matches the features of a task or the need to reorient attention to the target when such capture occurs. In our paradigm, the locations of targets were unpredictable. Successful target localization, then, required that participants direct covert attention to the target location in a stimulus-driven manner. Because this requirement falls nicely within the described function of both the frontal eye fields and inferior frontal gyrus, it seems very likely that the practice-related changes we observed in the function of these regions reflect a practice mediated change in their recruitment to subserve stimulus-driven covert orientation of attention.

The fact that these regions are associated with shifting and orienting attention in young adults (e.g., Corbetta & Shulman, 2002) resolves an apparent paradox in our results: how a behavioral practice effect that appears to be visually specific can have neural correlates outside of visual cortex. Because the behavioral data showed that practice-related effects were generalized across conditions, we conclude that practice with the FFOV task has its largest effect on processes of visual attention and perception. Previous training data collected in young adults suggests that the neural correlates of these findings should occur in visual cortex (Kelly & Garavan, 2005). Although we did find some evidence of training-related decrease in the ventral visual cortex that are strongly reminiscent of the neural correlates of repetition priming (e.g., Sayers & Grill-Spector, 2006), our strongest findings were in prefrontal regions. We think that practice in the FFOV task affects the processes by which older adults shift attention among locations in the visual world. Our neuroimaging data show us that the neural effects of practice in the FFOV task are most visible in modality nonspecific processors. Future research should examine whether the changes in these neural regions affect the performance of nonvisual tasks that require covert shifts of attention.

We found a number of other regions that showed practice-related changes in activation that were not significantly correlated with practice-related changes in task performance as measured outside of the scanner. We note that regions in the right superior and inferior parietal lobules are frequently associated with covert orienting of attention (for reviews, see Corbetta, 1998; Corbetta & Shulman, 2002), and training-related changes revealed by our study likely reflect greater recruitment of the attentional system after training in the FFOV task.

Three methodological challenges that we encountered both limit our conclusions and serve as cautionary tales to other researchers. First, the FFOV task demands that participants make no eye movements during performance. During fMRI scanning, however, nearly half of our older adult participants were unable to perform the demanding dual-task condition at the maximum exposure duration that precluded eye movements. Because meaningful analysis of our data required that each participant perform a minimum number of trials correctly, we discarded data from participants with very high error rates. Unfortunately, this problem prevented us from including in our analysis data from those participants who might benefit most from FFOV practice. Future researchers may be able to take

advantage of the advancement of concurrent eye-tracking and fMRI measurements to design paradigms that both constrain eye movements and are more easily negotiated by older adults. Second, we found differences in the attrition rate of adults in the practice and control groups. This was in part due to greater intolerance for the MRI environment in the control group and in part due to greater drop-out rates among control participants. Future researchers could potentially use MRI pretraining before group assignment to ensure that all participants assigned to a practice condition are MRI tolerant. Control participants should also participate in practice sessions with a different computer-based task (such as computer solitaire) to reduce the likelihood that they surmise their status as control participants and to equate their contact with researchers with that of members of the practice group.

The specific nature of our practice effects is the third methodological problem we encountered. We failed to find evidence of transfer of behavioral practice effects between two similar versions of the FFOV task despite a clear interaction between FFOV practice and testing session in the neural data. One possibility is that the large improvements in performance shown by all participants overshadowed practice-specific effects, perhaps as a result of improved comfort in the fMRI environment. fMRI pretraining may again resolve this issue. An alternative possibility, and the one we believe most likely, is that practice-related changes in neural function are more robust to small changes in task-design and task environment than are changes in behavior. Certainly any changes in behavior must be driven by changes in neural function, so it is possible that fMRI is simply a more sensitive measure of these changes than is behavioral testing. The final possibility is that the neural changes we observed would result from practice in any visual computer task, and that our behavioral training paradigm produced no specific practice effects that generalized beyond itself. We think this is unlikely to be the case, particularly in those structures in which we observed a correlation between behavioral improvements outside the fMRI and changes in activation measured by the fMRI. Again, engaging members of the control group in a visual computer game would eliminate this possible explanation.

Taken together, our behavioral and neuroimaging data suggest that practice with the FFOV task improves older adults' ability to orient attention to task-relevant visual stimuli. Differences between practice and control groups in the behavioral data collected outside of the scanner demonstrated that practice tended to improve performance generally, suggesting that multiple sessions of FFOV practice operate on processes of visual attention and perception. Neuroimaging data revealed increased recruitment of right ventral precentral gyrus and right inferior frontal gyrus to be the neural correlates of these improvements. Because neuroimaging research with young adults has associated activity in these regions with covert shifting and orienting of spatial attention, we interpret our findings as indicating that FFOV practice operates on brain regions that support operations of covert attention and attentional gating. These practice-related changes in brain activation are correlated with improvements in task performance as measured outside of the scanner, indicating that they play a significant role in increasing older adults' ability to orient attention to stimuli throughout the visual field.

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APPENDIX

Neuropsychological Testing

Each participant underwent testing in a battery of neuropsychological tasks. These included the Modified Mini-Mental State Exam, digits forward, digits backward, Kaufman Brief Intelligence Test (Kaufman & Kaufman, 1990), a perceptual motor skills battery, computation span, and the trail-making task.

We performed one-way analyses of variance on the neuropsychological data from these 45 participants to test for any differences between participants whose magnetic resonance imaging (MRI) data we included in our study and those whose MRI data we did not include. None of the tests showed a reliable difference between the groups, indicating that participants differed only their ability to perform the FFOV task, not on other measures of general cognitive function (see Table A1).

Behavioral Testing Results

We report testing results for 41 participants at the first behavioral testing session (we lost data from 4 participants due to computer user error). We calculated accuracy in each condition and subjected these data to a mixed-mode analysis of variance using the between-subjects factor MRI data (used, rejected) and the within-subjects factors exposure time (160 ms, 213 ms, 260 ms), dual-task condition (single, dual), task (central, peripheral), and line position (proximal, distal). Because the purpose of this analysis is to determine whether differences between participants whose MRI data was and was not rejected persisted in the performance of the behavioral pretest, we report only results related to the MRI data factor. We found a marginally significant interaction between the factors MRI data and exposure time, $F(2, 78) = 3.8$, $p < .03$. Neuman–Keuls pairwise comparisons revealed that participants whose MRI data was usable were more accurate (68%) than were those participants whose MRI data was not usable (63%) with 260 ms of exposure ($p < .05$). Participants whose MRI data was usable were more accurate (64%) than were those participants whose MRI data was not usable (60%) with 213 ms of exposure ($p < .05$). The two groups did not differ in the accuracy of their responses to trials with exposures of 160 ms ($p > .29$). We also found a marginally significant interaction among the factors MRI data, exposure duration, and line position, $F(2,78) = 2.65$, $p < .08$. Neumann–Keuls pairwise comparisons revealed that participants whose MRI data was included were more accurate for both proximally (70%) and

Table A1. Demographic Differences Between Participants Whose Magnetic Resonance Imaging (MRI) Data We Used and Whose Data We Rejected

Measure	MRI Data Used		MRI Data Rejected	
	M	SD	M	SD
Age (y)	66.75	6.92	67.17	4.93
Education (y)	15.91	3.46	14.94	2.39
Modified Mini-Mental State Exam	55.14	1.82	54.50	1.65
Digit Span				
Forward	7.96	2.69	7.67	1.64
Backward	6.79	2.32	6.22	2.56
Kaufman Brief Intelligence Test				
Composite	115.39	10.85	114.44	5.02
Verbal	112.86	13.66	114.17	6.85
Matrices	113.54	12.63	111.83	5.17
Perceptual Skills				
Box completion	40.11	12.23	41.78	13.22
Digit copying	65.96	11.96	69.28	12.15
Digit symbol translation	34.89	7.21	34.94	8.16
Sequential complexity	37.82	7.60	36.56	10.49
Computation span	2.86	1.04	2.67	1.24
Trail-making task				
Trails A	37.61	11.23	36.83	9.18
Trails B	73.32	29.83	79.83	25.98
Letter comparison				
Three items	15.93	3.09	15.72	3.68
Six items	8.04	2.50	8.28	3.68
Nine items	5.86	1.56	6.50	1.72
Stroop				
Reading	94.14	8.86	94.67	9.94
Color naming	70.75	13.49	66.56	19.85
Interference	36.43	9.24	35.39	11.84
Stroop effect*	0.36	0.10	0.33	0.12

Notes: M = mean; SD = standard deviation.

*The Stroop effect was calculated by subtracting the number of color words in colored ink read from the number of ink colors named and dividing this by the number of color words in black ink read.

There were no significant differences between the groups.

distally (66%) located lines than were participants whose data was not included (proximal = 66%, distal = 60%) when exposure duration was 260 ms ($p < .05$). Participants whose data was included were also more accurate for proximally located lines (68%) than were participants whose data was not included (61%) when exposure duration was 213 ms ($p < .05$). Accuracy did not differ between the groups for the other conditions ($p > .19$). No other main effects of, or interactions with, the MRI data factor met or approached conventional levels of significance. Because the slow exposure duration was closest to that used in MRI testing, these data suggest that differences in the accuracy with which participants performed the FFOV task in the MRI environment persisted during behavioral testing in a slightly different paradigm.