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Age-related variability in performance of a motor action selection task is related to differences in brain function and structure among older adults

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Abstract

Task performance for behaviors that engage motor cognitive processes may be particularly sensitive to age-related changes. One well-studied model of cognitive motor function involves engagement of action selection (AS) processes. In young adults, task conditions that add AS demands result in increased preparation times and greater engagement of bilateral dorsal premotor (PMd) and parietal cortices. The current study investigated the behavioral and neural response to a change in motor cognitive demands in older adults through the addition of AS to a movement task. Sixteen older adults made a joystick movement under two conditions during functional magnetic resonance imaging. In the AS condition, participants moved right or left based on an abstract rule; in the execution only (EO) condition, participants moved in the same direction on every trial. Across participants, the AS condition, as compared to the EO condition, was associated with longer reaction time and increased activation of left inferior parietal lobule. Variability in behavioral response to the AS task between participants related to differences in brain function and structure. Overall, individuals with poorer AS task performance showed greater activation in left PMd and dorsolateral prefrontal cortex and decreased structural integrity of white matter tracts that connect sensorimotor, frontal, and parietal regions--keys regions for AS task performance. Additionally, two distinct patterns of functional connectivity were found. Participants with a pattern of decreased primary motor-PMd connectivity in response to the AS condition, compared to those with a pattern of increased connectivity, were older and had poorer behavioral performance. These neural changes in response to increased motor cognitive demands may be a marker for age-related changes in the motor system and have an impact on the learning of novel, complex motor skills in older adults.

Keywords

action selection; movement; aging; imaging; functional connectivity

1. Introduction

The performance of skilled motor actions declines with age, which has direct implications for the performance of everyday functional activities (Seidler et al., 2010). Older adults tend

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to move slower than younger adults with decreased coordination and less smoothness (Cooke et al., 1989; Ketcham et al., 2002; Poston et al., 2009; Seidler et al., 2002). This decline in motor skill performance with age corresponds to changes in the peripheral and central neural structures that support movement (Seidler et al., 2010; Ward, 2006). Often cited changes in brain activation for the performance of motor skills in older individuals include an overall increase in the magnitude of brain activation compared to young adults and an increase in recruitment of brain regions ipsilateral to the side of movement (Heuninckx et al., 2008; Mattay et al., 2002; Noble et al., 2011; Ward et al., 2008). These changes in brain activation during the performance of motor tasks with age may reflect neural compensation in order to maintain performance level or age-related pathological changes that correspond to performance decline (Cabeza et al., 2002; Cappell et al., 2010; Mattay et al., 2006).

Interaction of the motor and cognitive systems is thought to increase with age (Li and Lindenberger, 2002). Experimental tasks that systematically increase motor cognitive demands may provide insights into the behavioral and neural consequences of aging on the motor system that are not apparent when only simple tasks are performed (Heuninckx et al., 2005; Ward et al., 2008). Therefore, when investigating the effect of aging on the motor system, tasks that are more cognitively demanding offer a unique opportunity to determine age-related changes. One well-studied model of cognitive motor function in young adults involves adding action selection demands to movement. Task conditions that require action selection (AS) based on an abstract, visual-based rule lead to longer preparation time compared with simple motor execution tasks with a corresponding increase in activation of bilateral dorsal premotor (PMd) and bilateral parietal cortices in young adults (Grafton et al., 1998a; Grol et al., 2006; O'Shea et al., 2007a; Toni et al., 2002). Left PMd has been suggested as a key resource for motor AS; when activity in left PMd is disrupted, AS performance degrades (Johansen-Berg et al., 2002; O'Shea et al., 2007a; Rushworth et al., 2003). However, the neural correlates of AS and the role of PMd for AS in older adults have not been reported.

The aging process varies between individuals. It has been proposed that neurophysiological measures of aging may better reflect age-related changes in the motor system than chronological age (Talelli et al., 2008). In young adults, variability in the functional and structural connectivity between PMd and primary motor cortex (M1) has been shown to correlate with motor AS task performance between individuals (Boorman et al., 2007; O'Shea et al., 2007b); greater connectivity between these regions correlated with faster reaction times. Currently, however, it is not known how variability in AS task performance between individuals relates to brain function and structure in older adults. Understanding the neural correlates of age-related changes in AS task performance may provide insight into variability in the aging process, as well as in disease expression for conditions that affect the elderly such as stroke.

The purpose of this study was to determine the behavioral and neural response to a change in motor cognitive demands through the addition of AS to a movement task in older adults. Functional magnetic resonance imaging (fMRI) during task performance was used to quantify brain function, and diffusion tensor imaging (DTI) was used to quantify white matter structure. We hypothesized that individuals would show a significant increase in planning time that corresponded to an increase in bilateral PMd and parietal cortex activation for AS compared to simple movement execution, similar to previous research in young adults (Grafton et al., 1998a; Grol et al., 2006; O'Shea et al., 2007a; Toni et al., 2002). We also hypothesized that variability in AS task performance between individuals would correlate with differences in brain function and structure, specifically within PMd. Since AS task performance could have had a positive or negative correlation with PMd

activation, this behavior-brain function hypothesis was two-tailed. Finally, we hypothesized that white matter structure in PMd and motor regions would negatively correlate with AS task performance such that individuals with better task performance would have greater white matter integrity in these regions.

2. Materials and Methods

2.1 Participants

Sixteen older adults (mean age ± standard deviation: 65 ± 9 years, range 48-77; 10 females) were recruited from the surrounding community. Participants had to be between the ages of 45 and 80 years of age and right-hand dominant (Oldfield, 1971). Potential participants were excluded if they had a Mini-Mental State Exam (Folstein et al., 1975) score less than 26, history of any neurologic diagnosis that affected movement of the arms, or contraindication to magnetic resonance image (MRI) (Kleim et al., 2007). All participants provided informed consent on a form approved by the university institutional review board.

2.2 Motor Task

All participants performed the motor task with the dominant, right hand. The task involved right or left movement of a standard joystick based on a visual cue in two different conditions. In the action selection (AS) condition, the individual moved right or left based on an abstract rule (Fig. 1). When a small square or large circle was shown, a joystick movement to the right was made; when a large square or small circle was shown, a joystick movement to the left was made. Small cues were 50 × 50 pixels in size while the large cues were 200 × 200 pixels. In the execution only (EO) condition, the visual cues were the same, however, the participant made a joystick movement in the same direction on every trial irrespective of the size/shape of the cue. Movement direction for EO was counterbalanced across participants. In both conditions, a single cue was presented for 2 sec in a pseudorandom order such that each cue was presented six times in each block (36 trials per block). The inter-trial interval varied between 2.0 and 3.25 sec to minimize anticipatory responses prior to the cue.

Prior to MRI, a training session in the laboratory was completed to ensure understanding of both task conditions. First, verbal and visual instruction on the AS condition was provided followed by a practice block of the AS condition. Three blocks of each condition were then completed in alternating order; the condition completed in the first block (AS/EO) was counterbalanced across participants. After completion of the training blocks, the participant practiced the MRI version of the task. This version alternated periods of movement (cues were green) with periods of view only (cues were red) in a block design (see below) and included a total of 10 movement trials (5 trials per movement epoch).

2.3 Brain Imaging

All brain imaging sessions were performed on a 3T Achieva MRI scanner (Phillips Medical System, Best, Netherlands). Functional MRI data were acquired using a block design while the participants performed the AS and EO tasks with an MRI compatible joystick (Current Designs, Philadelphia, PA). Periods of movement (Move, 24 sec) alternated with periods of view only (View, 24 sec) with a fixation period (red cross, 8 sec) between each epoch. Cue duration (2 sec) and the inter-trial interval (varied between 2.0 and 3.5 sec) were the same as during practice in the laboratory. Just prior to entering the scanner, the movement rule for the AS condition was reviewed; no additional reminders of the rule were provided during scanning. Each participant completed four fMRI runs, two in the AS condition and two in the EO condition in alternating order; the condition completed in the first run (AS/EO) was counterbalanced across participants. Functional runs lasted for 2 minutes 10 seconds during

which 65 brain volumes were acquired (TR=2000 ms, TE=30 ms); each volume included 31 slices that were 4 mm thick with a slice gap of 1 mm (acquisition voxel size 2.5 mm × 2.5 mm × 4 mm). Next, a high resolution structural MPRAGE image was acquired (TR=8,400 ms, TE=3.9 ms) which included 150, 1 mm thick slices with no interslice gap (acquisition voxel size 1 mm × 1 mm × 1 mm). Finally, DTI images were obtained using echo planar imaging (EPI) (TR=11,190 ms, TE=69 ms) and included 60, 2 mm thick slices with no interslice gap (acquisition voxel size 2 mm × 2 mm × 2 mm). Diffusion images included 32 noncollinear directions with a *b* value of 800 s/mm^2 and a single volume with no diffusion weighting (*b*=0). Total scan time for each session was approximately 45 minutes.

2.4 Data Analysis

2.4.1 Behavioral Data—Data from the joystick were used to determine task accuracy, reaction time (RT), and movement time using a custom script in Matlab (Matworks, Inc., Natick, MA). Position data (x,y) were recorded throughout each trial (60 Hz in the laboratory, 30 Hz in the MRI) and used to derive movement velocity (Winter, 2005). Reaction time, the primary behavioral outcome measure, was the time between cue presentation and movement onset. Movement onset was determined by searching backward in time from initial peak velocity until velocity dropped below 5°/sec for two consecutive samples or the change in velocity dropped below 1°/sec for two consecutive samples, whichever was identified first. Movement offset was determined by searching forward in time from peak velocity until velocity dropped below 10°/sec for two consecutive samples. AS RT was normalized to EO RT to determine RT cost (AS RT – EO RT), a measure of the relative increase in planning time for the AS condition for each participant. Movement time was the time between movement onset and movement offset. All movement data were analyzed with a repeated measures analysis of variance that included two factors (condition, trial block). Data collected during fMRI were analyzed separately with a paired *t*-test to determine differences between conditions during scanning. Significant level was set at $p<0.05$ for all statistical tests. JMP 8 (SAS, Cary, NC) statistical software was used for analyses.

2.4.2 Functional Imaging Data—All functional imaging data were analyzed using SPM8 (Wellcome Department of Cognitive Neurology, London, UK). First, volumes from each run were realigned to the first volume and resliced to account for motion artifact. The mean image for each participant was then normalized to the standard Montreal Neurological Institute (MNI) EPI template in SPM. The normalization parameters were then applied to all of the functional volumes for that participant, and the normalized images were resampled to 2 mm × 2 mm × 2 mm voxels. Images were then spatially smoothed with an isotropic Gaussian filter (FWHM=8 mm) and a temporal filter was applied (128 Hz) to remove low frequency confounds. Data from each functional run were inspected for outliers due to excessive head motion (>1mm translation or >0.2 radians rotation between each volume) and signal noise (Z>3 from the mean image intensity) using the Artifact Detection Tool toolbox (http://www.nitrc.org/projects/artifact_detect); outliers were deweighted during statistical analysis. Data from all participants and all runs were included in analyses.

First-level statistical analysis was performed separately for each participant using a general linear model (Friston et al., 1995a; Friston et al., 1995b). For each run, Move and View epochs were modeled separately against fixation for later contrast. To determine the regions active during each condition (EO, AS), Move was contrasted with View (Move>View); both runs for each condition were weighted equally in all contrasts. For first-level analyses, the first derivative of head motion for all six directions, which was uncorrelated with stimulus presentation, was added as a regressor of no interest to account for the effect of head motion in the data.

The contrast maps for each participant and each condition were moved to a second-level random effects analysis. To determine brain regions active during each condition, a one-sample *t*-test was used on the Move>View contrasts for EO and AS. Next, a paired *t*-test was used to determine differences in brain activation between conditions (EO>AS; AS>EO); movement time (mean during all fMRI trials) was included as a regressor of no interest to account for differences in movement response unrelated to RT. To examine the relationship between RT variability and brain activation between individuals, three separate regression analyses were performed: EO RT with the EO contrast map; AS RT with the AS contrast map; RT cost with the AS contrast map. Age and movement time were included as regressors of no interest for all regression analyses. For group comparisons, statistical significance was set at $p<0.001$ without correction for multiple comparisons. Clusters were considered significant at $p<0.05$ uncorrected for multiple comparisons.

Next, we performed a psychophysiological interaction (PPI) analysis to identify brain regions in which the connectivity with M1 and PMd changed as a function of task condition (Friston et al., 1997; Gitelman et al., 2003). PPI is a measure of functional connectivity that identifies changes in correlation between the seed region and other regions based on a psychological variable (e.g., task condition: EO, AS); analyses were carried out separately using M1 and PMd as seed regions. For each subject, after carrying out a GLM statistical analysis, the time series of the mean corrected, high-pass filtered BOLD signal was extracted from M1 and PMd (4 mm radius sphere centered on the group peak derived from average activation across conditions). This time series and the psychological vector of interest (action selection minus execution only) were used to create the PPI interaction term. The interaction term as well as the seed region time series and psychological vector were entered into a first-level model of connectivity. Brain areas showing an increase in connectivity with the seed region in the AS condition were determined by testing for significant positive changes in slope of the PPI regressor (*t*-contrast with +1 for the PPI regressor). Regions showing a decrease in connectivity with the seed regions in the AS condition were determined by testing for significant negative changes in slope of the PPI regressor (*t*-contrast −1 for the PPI regressor). Contrast images from both comparisons (increased connectivity in AS, decreased connectivity in AS) were then entered into separate second-level random effects analyses (one-sample *t*-test) to determine regions whose connectivity with M1 or PMd changed between task conditions. Statistical significance was set at $p<0.001$ without correction for multiple comparisons.

To further explore the relationship between variability in behavior and variability in brain activation, we examined the correlation between brain connectivity and RT. PPI analysis is designed to test for differences in the regression slope between the seed region and other brain areas based on task condition. Therefore, the time series data from one region of interest was plotted against the time series data of another region of interest and the slope of the regression line was extracted separately for each of the two conditions (EO, AS) (Lin et al., 2012). The change in slope from EO to AS was the measure used to define the effect of task condition on functional connectivity. If the slope increased, the activity in the two brain regions was more correlated in the AS condition than the EO condition. If the slope decreased, the activity between the two brain regions was less correlated in the AS condition. To determine if change in connectivity related to variability in task performance between participants, the change in slope between left M1 (centered on the group peak derived from average activation across conditions) and each region identified in the regression analysis was correlated with RT.

2.4.3 Diffusion Tensor Imaging Data—Voxelwise statistical analysis of fractional anisotropy (FA) was carried out using tract-based spatial statistics (TBSS) (Smith et al., 2006), which is part of FSL (FMRIB Center, Oxford, UK). Diffusion images were corrected

for eddy currents and head motion followed by removal of the skull and dura (Smith, 2002). FA images were created using DTIFit and individual maps were nonlinearly registered to a standard FA template using the FNIRT tool (Andersson et al., 2007a; Andersson et al., 2007b) which uses a b-spline representation of the registration warp field (Rueckert et al., 1999). FA is a measure of the structural integrity of white matter (Le Bihan and Johansen-Berg, 2012). Values range between 0 and 1 with higher values indicating greater structural integrity. Next, an across-subject mean FA image was calculated and used to generate an FA 'skeleton' (threshold at FA>0.2), which represents the center of all tracts common to the group. Each participant's maximum FA value nearest to the mean FA skeleton was projected onto the skeleton for statistical analyses.

Voxelwise, permutation-based nonparametric testing (Nichols and Holmes, 2002) (5000 permutations) was used to determine the relationship between task performance and white matter structure (FA values). Three measures of task performance from the first block of performance were separately analyzed with TBSS: EO RT; AS RT; and RT cost. The first block completed in the lab was chosen for TBSS analysis as it was expected that this block would best represent initial response to the experimental conditions. Clusters were considered significant at $p<0.05$ corrected for multiple comparisons using the threshold-free cluster enhancement correction.

3. Results

3.1 Motor Task Performance

Accuracy, RT, and RT cost in both conditions across blocks are shown in Figure 2. As expected, participants were very accurate during performance of the EO task (> 97%). Accuracy on the AS task was quite varied between participants during the practice block but improved over blocks such that task accuracy for the AS condition averaged 94% during fMRI scanning. As hypothesized, RT for the AS task was significantly longer than for the EO task ($p<0.0001$). Action selection RT significantly decreased over practice blocks ($p=0.0018$) while EO RT did not change ($p=0.3415$). Therefore, changes in RT cost over practice blocks ($p<0.0001$) were driven by faster RT during AS. Movement time did not change over practice blocks ($p=0.6081$) and did not significantly differ between conditions ($p=0.0844$; data not shown).

During fMRI, motor performance was stable and similar to performance in the lab. Reaction time for AS was significantly longer than for EO ($p<0.0001$) while movement time did not differ between conditions ($p=0.9471$). While reactions times for both conditions were longer during MRI testing compared with in the laboratory, RT cost during fMRI was consistent with the end of practice in the laboratory ($p=0.7741$). For the fMRI block, age did not correlate with EO RT ($r=0.205$, $p=0.447$) but did have a moderate correlation with AS RT ($r=0.508$, $p=0.044$) and RT cost ($r=0.494$, $p=0.052$).

3.2 Brain Activation During Task Performance

Brain activation during EO task performance is shown in Figure 3. Performance of a simple motor task (repetitive movement in the same direction) activated the anticipated motor network including left M1, PMd, supplementary motor and parietal cortices as well as the thalamus, basal ganglia, and right cerebellum. Overall, the same network of brain regions was activated during AS task performance (Fig. 3). The paired *t*-test between conditions revealed a significant cluster in the left inferior parietal lobule that was more active during AS than EO (Fig. 3, Table 1). A cluster in the same region in the right hemisphere was more active during AS but this region was not significant at the cluster level ($p=0.140$). No regions were more active during EO compared with AS ($p<0.001$ uncorrected).

Whole brain PPI analysis was carried out separately with left M1 (centered on group coordinates: −30 −26 52) and left PMd (group coordinates: −24 −6 52) used as the seed regions. This analysis was performed to determine changes in the correlation between M1/PMd and other brain regions based on task condition (EO>AS; AS>EO). There were no significant clusters ($p<0.001$ uncorrected) that changed their relationship with M1 or PMd between the EO and AS conditions for the group.

3.3 Neural Correlates of Inter-individual Variability in Task Performance

3.3.1 Functional Correlates—Whole brain regression analysis was run in order to determine if variability in task performance between subjects was related to variability in brain activation. First, RT cost was examined in relation to activation during the AS condition. Two significant clusters were found where activation significantly correlated with RT cost: left PMd and left dorsolateral prefrontal cortex (DLPFC) (Fig. 4, Table 1). Both of these clusters showed a positive correlation with RT cost, i.e., individuals who took relatively longer to prepare a response in the AS condition had greater activation in both PMd and DLPFC. When AS RT and EO RT were related to variability in brain activation, no significant clusters were found.

To determine if the connectivity between left PMd, DLPFC, and M1 varied with task performance, we extracted the slope of activation between regions for each condition. RT cost was used as the behavioral measure of task performance given that this was the only variable showing a significant activation-behavior correlation in the regression analysis above. The change in slope between pairs of brain regions (PMd-M1, DLPFC-M1, PMd-DLPFC) and RT cost was examined for significant correlations. When this relationship was studied across all participants, the change in connectivity between regions did not significantly correlate with RT cost. However, two distinct patterns of functional connectivity were identified in post-hoc analysis of the PMd-M1 connectivity data. One group of participants showed a pattern of increased connectivity from the EO to AS condition (n= 9) while the other group showed a pattern of decreased connectivity from EO to AS (n=7) (Fig. 5). The group with decreased connectivity during the AS condition had significantly higher RT cost ($p<0.05$) (Fig. 5C) and were older compared to the increased connectivity group (mean age ± standard deviation: increased connectivity group: 60.0 ± 9.7 years; decreased connectivity group: 70.1 ± 4.6 years; $p<0.03$). While the magnitude of activation in M1, PMd and DLPFC tended to be higher in the decreased connectivity group (Fig. 5C, bottom row), these differences in percent signal change between groups were not statistically significant ($p>0.29$ for all comparisons).

3.3.2 Structural Correlates—A whole brain TBSS analysis was used to determine if white matter structure in any regions correlated with task performance. There were no regions where FA had a significant correlation with EO RT. There was, however, a single, large cluster where FA had a significant, negative correlation with AS RT and RT cost that included a range of white matter regions in bilateral frontal, parietal, and occipital lobes (Fig. 6A). Specifically, several callosal and association fibers showed a significant relationship between FA and AS task performance: prefrontal and somatosensory regions of the corpus callosum, anterior limb of the internal capsule, inferior longitudinal fasciculus, inferior fronto-occipital fasciculus, and left superior longitudinal fasciculus. When age was added as a covariate in the TBSS analysis, no regions continued to be significant. Age had a significant, positive correlation with RT cost during the practice block ($r=0.701$, $p=0.0025$). Therefore, a follow-up analysis was done to investigate whether age alone correlated with white matter structural integrity. Several brain regions showed a negative correlation with age, and these regions overlapped significantly with the analysis of RT cost with FA (Fig. 6B). Therefore, the correlation between FA and RT cost may in part be driven by age. The

addition of gender as a covariate had no effect on the outcome of the any of the TBSS analyses performed.

4. Discussion

This study examined the neural correlates of motor action selection in older adults. The increase in motor preparation time to perform the AS task over simple movement execution (EO) corresponded to increased activation in the inferior parietal lobule, similar to previous reports in young adults (Grafton et al., 1998a; Grol et al., 2006; O'Shea et al., 2007a; Toni et al., 2002) and further supporting the role this region plays in visuomotor actions (Fogassi and Luppino, 2005; Grefkes and Fink, 2005). Additionally, differences in AS task performance between individuals were related to variability in the magnitude of brain activation, functional connectivity and white matter structural integrity. Overall, the findings of the current study suggest that variability in AS task performance relates to brain function and structure in older adults, and that these brain-behavior relationships may be a marker for age-related changes in the motor system.

Activation in both left PMd and left DLPFC had a positive correlation with AS task performance; poorer performers showed greater magnitude of activation in these regions. Previous studies that investigated the neural correlates of AS in young adults did not find DLPFC activation and did not relate variability in behavioral performance to variability in the magnitude of brain activation (Grafton et al., 1998b; Grol et al., 2006; O'Shea et al., 2007a; Toni et al., 2002). This pattern of increased activation with poorer AS task performance was not related to age (age was covaried out of the regression analysis) and may have been compensatory in nature in order to maintain task accuracy. Such findings are consistent with previous work in older adults that has reported increased PMd activation during simple motor execution tasks (Mattay et al., 2002; Ward and Frackowiak, 2003) and engagement of prefrontal regions for the performance of complex motor tasks (Heuninckx et al., 2005). Additionally, engagement of DLPFC by participants who were relatively poorer performers on the AS task suggests that these individuals required greater attentional and cognitive resources for task completion. Interaction of motor and cognitive systems increases with age (Heuninckx et al., 2005; Li and Lindenberger, 2002) and may serve as a neurophysiological marker of aging (Talelli et al., 2008).

Analysis of functional connectivity between left PMd and left M1 revealed two distinct patterns of brain function for performance of the AS task. The more successful pattern was associated with less RT cost and entailed increasing connectivity between PMd and M1 for AS compared with the easier EO task. Although a post-hoc observation, this pattern is consistent with previous studies in young adults that found increased functional and structural connectivity between PMd and M1 during AS correlated with better performance (Boorman et al., 2007; O'Shea et al., 2007b). The less successful pattern was associated with higher RT cost and involved decreasing connectivity between PMd and M1 for the AS task. This altered control pattern of decreased PMd-M1 functional connectivity may reflect age related changes in neural recruitment for performance of a motor AS task; individuals who showed a decrease in connectivity were significantly older than individuals who showed an increase in connectivity. It is also possible that the differences in functional connectivity reflect varied levels of task difficulty/phase of learning as connectivity can change over a period of motor task practice (Lin et al., 2012; Wu et al., 2008). Note that the whole-brain PPI analysis did not find any significant clusters that showed a change in connectivity with M1 or PMd between the EO and AS conditions. This negative finding reflects the fact that some individuals showed an increase in connectivity with AS while other individuals showed a decrease in connectivity with AS making the group effect null.

White matter structure as measured by FA correlated with AS task performance in a widespread set of areas including the prefrontal and sensorimotor regions of the corpus callosum and long association fibers that connect frontal and parietal/occipital regions, areas which were also identified with fMRI. The relationship between FA and behavior, however, was not present when age was included a covariate. In fact, these same regions showed a significant, negative relationship with age suggesting that increases in RT cost were related to age-driven changes in FA. These findings are consistent with previous work that has linked structural changes in the corpus callosum with age-related changes in motor function (Fling et al., 2011) and in fronto-parietal association fibers with age-related changes in working memory (Charlton et al., 2010; Sasson et al., 2010). There were no white matter regions that significantly correlated with EO task performance, which is similar to a simple RT task. The use of complex tasks that engage motor cognitive regions in addition to motor execution regions may provide greater insight into the structural brain correlates of motor function with age.

Action selection was associated with increased activation in the left IPL for the group. The AS condition required the mover to link the visual cue to the correct movement response while the EO condition did not. Increased activation in the IPL for the AS condition likely relates to the role this region plays in mapping visual cues to motor responses (Grol et al., 2006; Jiang and Kanwisher, 2003; Schumacher et al., 2003). There was not a significant increase in PMd activation with AS task performance for the group as hypothesized, however, and as has been previously reported in young adults (Grafton et al., 1998a; Grol et al., 2006; O'Shea et al., 2007a; Toni et al., 2002). There are several possible reasons that PMd did not play the anticipated role for motor AS in this group of older adults. First, left PMd was significantly activated during both the EO and AS tasks in the current experiment. Performance of simple motor execution tasks can lead to greater PMd activation in older adults compared to younger adults (Mattay et al., 2002; Ward and Frackowiak, 2003). Activation during EO may have made finding statistically significant increases in PMd activation during AS difficult. Second, modulation of PMd activation to meet task demands may be altered in older adults. Previous research has shown that older adults show a decrease in modulation of brain activation to meet the demands of a motor execution task of increasing force requirements (Ward et al., 2008). A decreased ability to modulate PMd activation may have led individuals to rely on other brain regions. Third, left PMd activation during task performance may have reflected the stage of AS task learning. Brain activation can change from the early stages to the later stages of motor skill learning (Floyer-Lea and Matthews, 2004; Karni et al., 1995; Lin et al., 2011; Wu et al., 2004). It is possible that the lack of increased PMd activation during AS in the current study reflects a relatively early stage of learning in this group of older adults. Future research might examine how brain activation during AS changes throughout the learning process in older individuals.

In conclusion, older adults showed an increase in planning time and engaged parietal cortex to successfully perform a motor AS task. Individuals who took longer to respond, and therefore had poorer performance, showed decreased connectivity between PMd and M1, increased magnitude of activation in PMd and DLPFC, and decreased white matter structural integrity in tracts that connect sensorimotor, frontal, and parietal regions. Overall, these neural changes with AS task performance may be a marker for age-related changes to the motor system and provide a basis for future research investigating individual responses to motor learning conditions that engage AS processes.

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Highlights

- Motor action selection engaged the inferior parietal lobule in older adults.
- Higher activation in premotor and prefrontal cortex related to worse performance.
- PMd-M1connectivity changed for action selection and varied between participants.

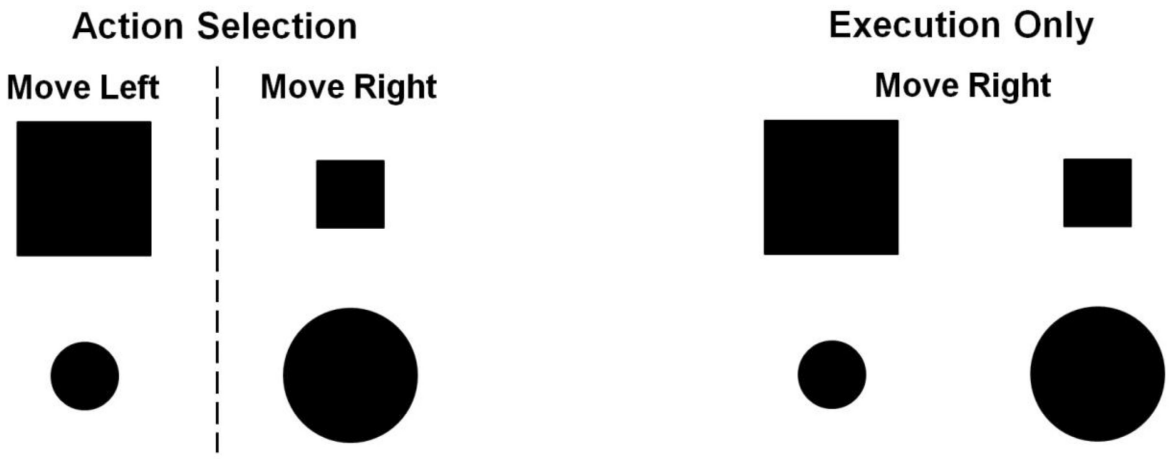

Figure 1.
Participants moved the joystick under two experimental conditions. During *action selection*, movement direction was dictated by an abstract rule (large square or small circle=move left; small square or large circle=move right). During *execution only*, movement direction was the same on every trial regardless of visual cue. Movement direction (right/left) for execution only was counterbalance across participants.

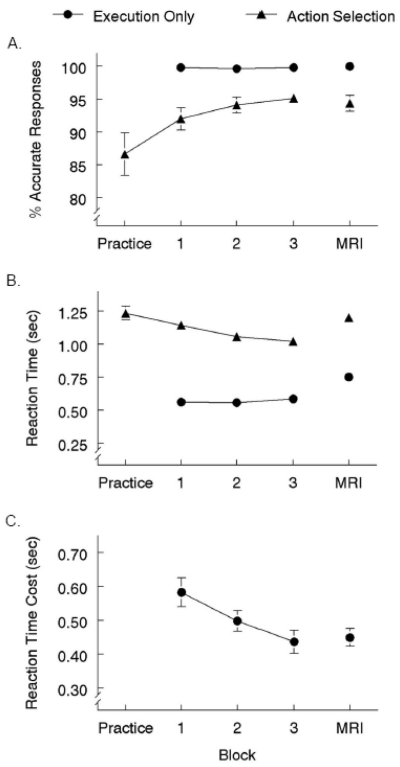

Figure 2.

Behavioral performance for both experimental conditions shown for task accuracy (A), reaction time (B), and reaction time cost (C). Each data point represents the group mean with standard error bars. Practice through Block 3 was completed in the laboratory before MRI.

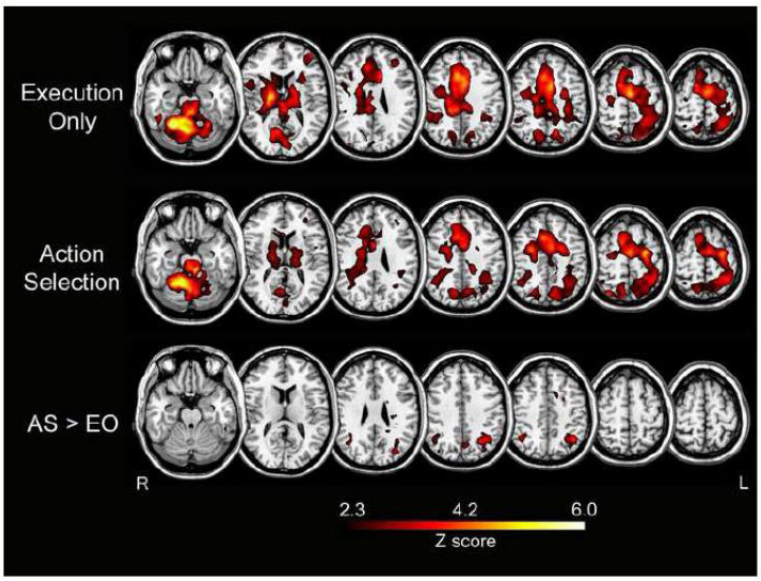

Figure 3.
Results of one-sample *t*-test for each condition (execution only, action selection) and for paired *t*-test comparing action selection to execution only (AS>EO) with movement time added as a regressor of no interest. There were no regions significantly more active during execution only compared to action selection.

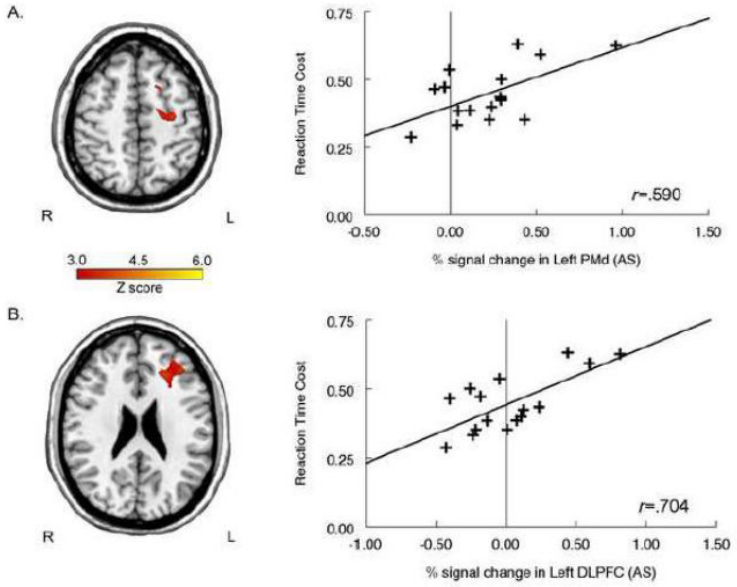

Figure 4.

Results of whole brain regression analysis between reaction time (RT) cost during MRI and brain activation during the action selection condition with age and movement time included as regressors of no interest: A) left dorsal premotor cortex (PMd), and B) left dorsolateral premotor cortex (DLPFC). For scatter plots, percent signal change was extracted from the significant cluster ($p<0.001$ uncorrected for multiple comparisons) during action selection; each data point represents performance for a single participant.

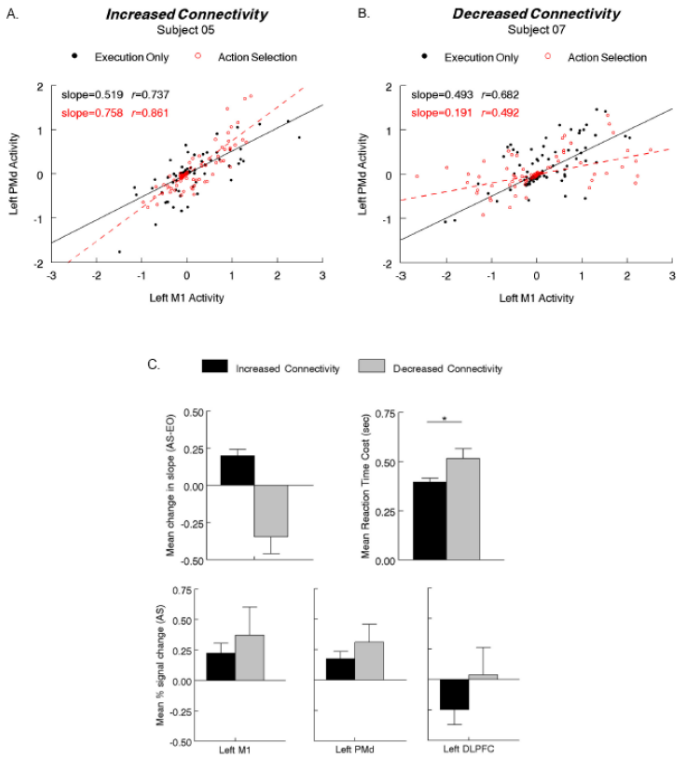

Figure 5.

Results of psychophysiological interaction analysis. Connectivity between left dorsal premotor (PMd) and left primary motor (M1) cortices during action selection compared to execution only increased for the participant shown in A and decreased for the participant shown in B (each data point represents activity for a single brain volume). Slope and correlation coefficient (*r*) were extracted for each participant and condition. Participants were split into two subgroups based on the direction of change in M1-PMd connectivity for the action selection task: Increased Connectivity (n=9) and Decreased Connectivity (n=7). The Increased Connectivity subgroup had significantly lower reaction time cost (C); trends for differences in activation between these two subgroups are presented in the bottom row.

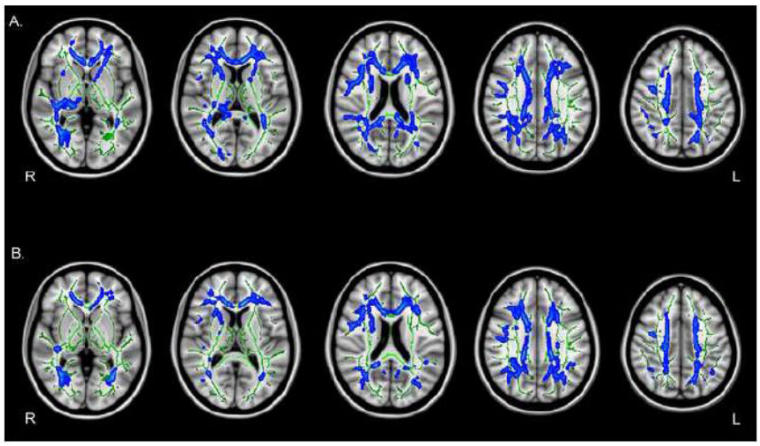

Figure 6.

Tract based spatial statistics (TBSS) results comparing variability in fractional anisotropy (FA) with variability in reaction time (RT) cost during the initial practice block (A), and with age (B). Mean FA skeleton (green) and TBSS results (negative correlation with FA in blue) are shown on a template brain in MNI space on axial slices.

Table 1

Location of significant clusters for group and regression analyses

				MNI Coordinates		
	Brain Region	**Volume**	**Peak Z**	**x**	**y**	**z**
Group AS>EO	L inferior parietal lobule	250	4.54	−38	−58	44
Regression AS with RT Cost	L dorsolateral prefrontal cortex	368	4.01	−28	44	36
	L dorsal premotor	121	3.78	−32	−12	52

All clusters were significant at $p<0.001$ uncorrected for multiple comparisons. Group Analysis=paired *t*-test comparing two conditions; Regression Analysis=whole brain regression between activation during AS and RT Cost. Volume=number of 8 mm^3 voxels in cluster; Peak Z=peak Z value within the cluster; L=Left; AS=Action Selection; EO=Execution Only; RT=Reaction Time