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Motor asymmetry reduction in older adults

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ABSTRACT

While cerebral lateralization has previously been well documented for many neurobehavioral functions, recent research has shown that as people age, formerly lateralized processes recruit more symmetric patterns of neural activity. Such findings provide the foundation for the model of hemispheric asymmetry reduction in older adults, or "HAROLD" [4]. Previous studies that have measured reaction time and movement time have suggested that aging does not affect manual asymmetries. However, whether these findings can be extended to kinematic variables associated with motor coordination remains largely unknown. The purpose of the current study is to determine whether asymmetries in intralimb coordination are also reduced during the aging process. We examined multidirectional reaching in two different right handed age groups, a younger group from 20 to 40 years of age, and an older group, from 60 to 80 years of age. Measures of final position accuracy, precision, and trajectory linearity showed robust asymmetries between the left and right arm groups of young adults. However, the trajectories and accuracies of the older subjects were symmetric, such that our dependent measures were not significantly different between the right and left arm groups. Our findings extend the HAROLD model to motor behavior, suggesting that aging results in decrements in motor lateralization.

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Handedness, the tendency to favor one arm in performing selected tasks, is a prominent feature of human motor control. We previously hypothesized that handedness might reflect a functional optimization process through which control of limb impedance and trajectory have become differentially specialized [1,2,24,25,27,28,33,34]. We termed this hypothesis *Dynamic Dominance* because of evidence that dominant arm coordination is associated with more efficient coordination of muscle torques with internal and environmental dynamics. In our previous studies, this difference in coordination was reflected by robust direction-dependent differences in the linearity of right and left arm reaching movements.

Research conducted over the past decade, primarily by Cabeza et al. [3–6,10,17], has shown age-related reductions in hemispheric lateralization for cognitive processes. According to these studies, neural lateralization for certain types of memory becomes substantially reduced in people who are older than 65 years of age. These findings, based on brain imaging, have led to the model of hemispheric asymmetry reduction in older adults, or "HAROLD". Previous studies reported that while age increases reaction and movement time, asymmetries in these measures do not change with age [8,11]. However, those studies did not assess the effects of aging on kinematic variables associated with motor coordination that are implicated by our Dynamic Dominance Model. We now ask whether aging might be associated with changes in asymmetries in the trajectories and accuracies of reaching movements. In order to examine this hypothesis, we tested a young group, from 20 to 40 years of age, and an older group, from 60 to 80 years of age. We examined how subjects from these age groups coordinated multidirectional reaching movements in the horizontal plane.

Young (28 ± 6 years; $n = 22$, 9 males) and old (68 ± 3 years; $n = 22$, 11 males) healthy individuals were paid to participate in this study, which was conducted in accordance with the Declaration of Helsinki. Each individual signed the consent form approved by the Institutional Review Board of the Pennsylvania State University and the New Mexico Veterans Affairs Healthcare System. Subjects' weight and height were on average 62 ± 9 kg and 1.62 ± 0.04 m for young, and 67 ± 6 kg and 1.54 ± 0.05 m for old group. All participants performed within normal limits (>27) on the Mini-Mental State Examination [9], and had normal visual acuity (uncorrected or corrected with lenses). They were all right-handed according to the modified Edinburgh Inventory [21], and naive to the purpose of the experiment. Each age group was separated into 2 demograph-

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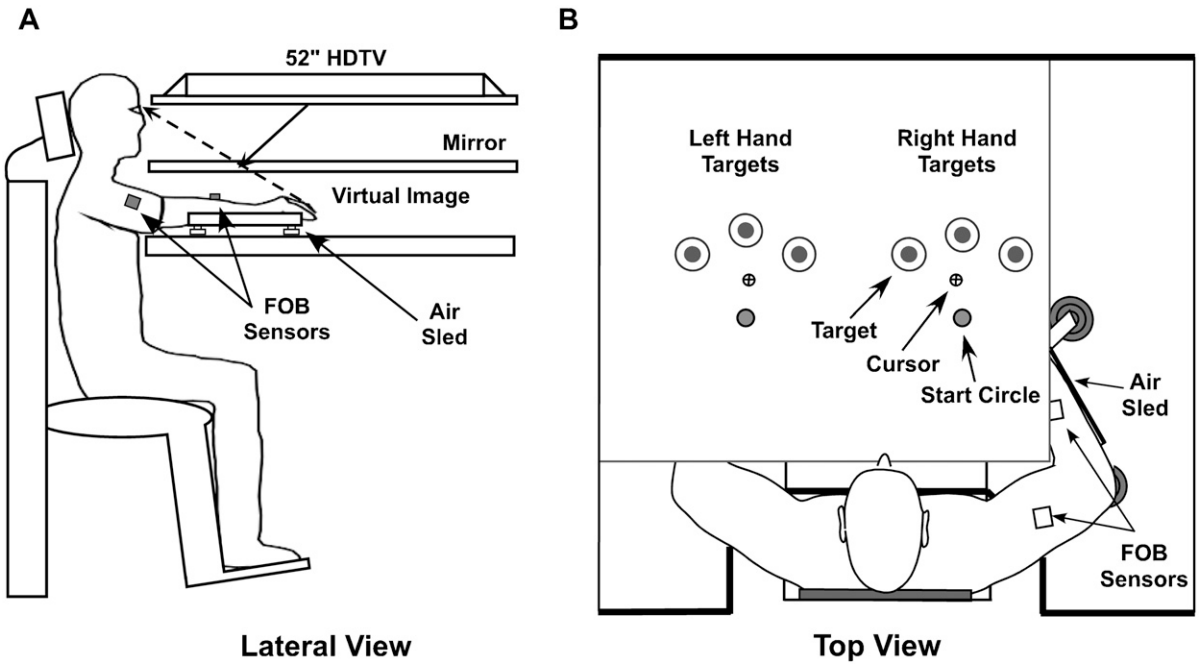

Fig. 1. (A) *Side view*: subjects were seated in a chair with the arm supported by an air jet system that removed the effects of friction on arm movement. Targets and the cursor representing hand position were reflected in a mirror placed above the arm. (B) *Top view*: the positions of the start and target circles, and the Flock of Birds sensors are shown.

ically matched groups, one that performed the task with the left, and the other with the right arm. This was necessary to prevent interlimb transfer of learning between the arms [28].

Fig. 1 illustrates the experimental setup. Participants sat facing a projection screen with either their left or right arm positioned just below shoulder height, by an air-bearing support that reduced the effects of gravity and friction. Details of this set-up have recently been published elsewhere [20]. The displayed cursor was the only visual feedback available to the subjects during the experiment. All joints distal to the elbow were immobilized using an adjustable brace. Position and orientation of each arm segment were sampled using a Flock of birds® (Ascension-Technology) magnetic 6-DOF movement recording system.

We presented three targets: *central*, oriented 90° relative to the horizontal axis; *lateral*, rotated 40° laterally from *central*; *medial*, rotated 40° medially from *central*. All three targets were 4.5 cm in diameter and 16 cm from the start circle (2 cm in diameter) position. Prior to movement, a cursor and a start circle were shown on the screen. The target appeared simultaneously with a "go" tone, once the subject held the cursor within the starting circle for 500 ms. Subjects were to move the cursor to the target using a single, uncorrected, rapid motion. Feedback regarding the fingertip position (cursor) was given to allow subjects' to locate the start position and then removed at the "go" signal. No visual feedback of the cursor was given during the movement. Although explicit knowledge of results was not provided at the end of the movement, subjects received a numerical score at the end of each trial to maintain motivation, based on the location of the index finger relative to the center of the target at movement end. Final position errors of less than 2.25 cm (target radius) were awarded 10 points, while errors between 2.25 cm and 4.5 cm were awarded 3 points, and errors between 4.5 cm and 6.25 cm were awarded 1 point. Following the display of the numerical score after each trial, the cursor was redisplayed for accurate positioning of the fingertip back at the start circle for the next trial. The three targets were presented in a pseudorandom order over a session of 99 trials, such that no single target was presented consecutively. Subjects were given velocity feedback after each trial in the form of a thermometer-style display. In order to ensure similar speed movements between groups, points were only awarded for movements with peak velocities between 0.5 and 0.8 m/s. This range of movement speed was based on self-selected speeds of older subjects, derived from preliminary data. The speed range is somewhat slower than the range of speeds that are selected by younger subjects in similar tasks [25].

The 3D position of the index finger, wrist, elbow, and shoulder positions were calculated from sensor position and orientation data. These displacement time series were low-pass filtered at 8 Hz (3rd order, dual-pass Butterworth) and then differentiated to obtain velocity profiles. Movement initiation (movement start) was defined as the last minimum on the velocity profile, identified below 8% of peak tangentional velocity, prior to the time of peak velocity. Movement termination (movement end) was similarly defined as the first minimum on the velocity profile, identified below 8% of peak velocity, after the time of peak velocity.

The following measures were calculated for each trial: movement duration, absolute and variable final position error, peak tangential velocity, and hand path curvature. Movement duration was defined as the elapsed time from movement start to movement end, while relative deceleration duration was defined as the time between peak velocity and movement end, normalized by movement duration. Absolute error, a measure of accuracy, was calculated as the Euclidean distance from the position of the index fingertip at movement end (x_f, y_f) to the center of the target (x_t, y_t): $d = \sqrt{(x_t - x_f)^2 + (y_t - y_f)^2}$. Variable error, a measure of precision, was calculated as the Euclidean distance from the position of the index fingertip at movement end (x_f, y_f) to the mean position of the index fingertip at movement end (x_m, y_m): $d = \sqrt{(x_m - x_f)^2 + (y_m - y_f)^2}$. This mean position of the index fingertip at movement end (x_m, y_m) was calculated by averaging coordinates (x and y) of the index fingertip at movement end across all trials within each target. Our measure of hand path curvature was calculated as the minor axis divided by the major axis of the hand path [1,26].

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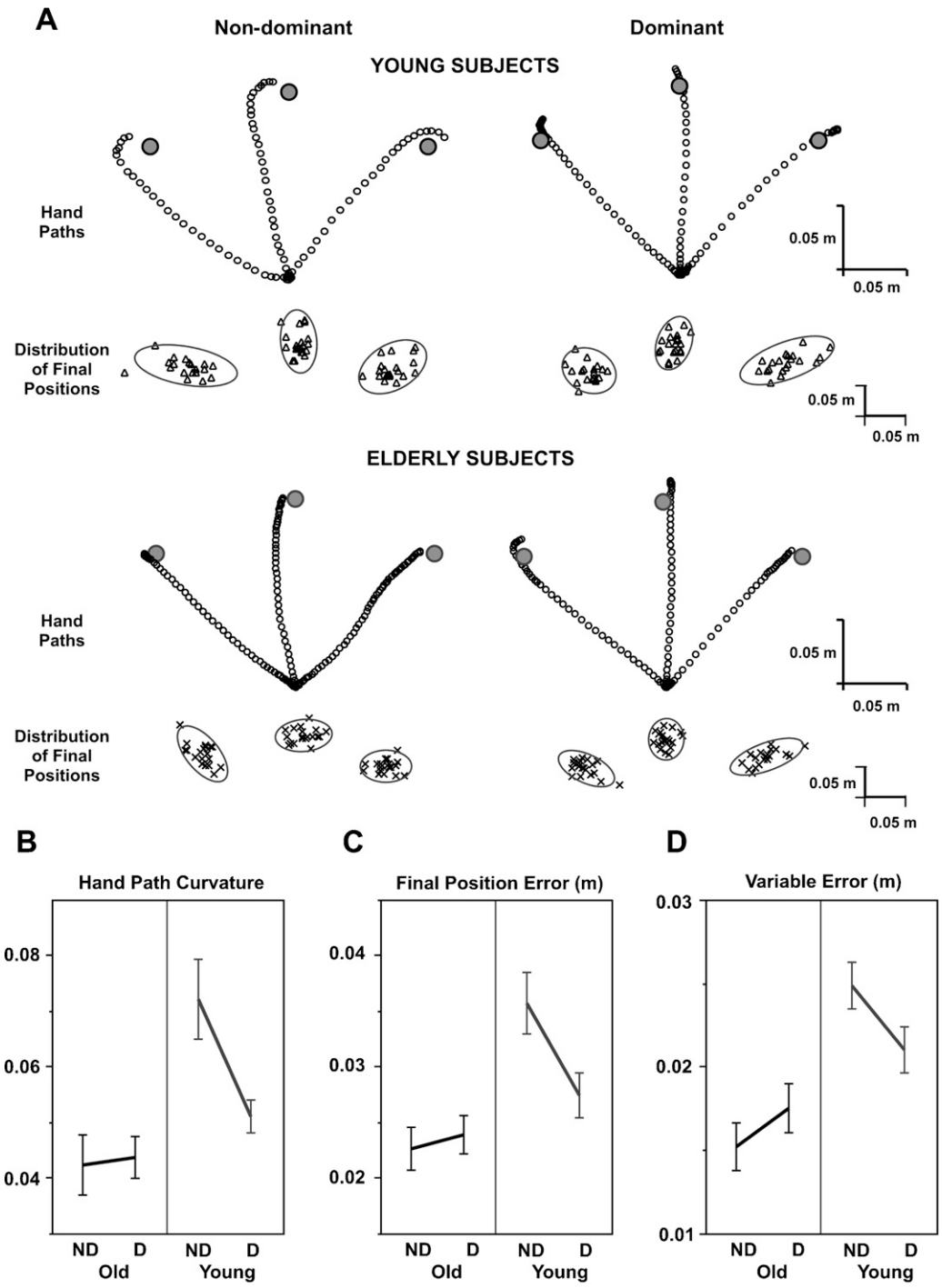

Fig. 2. (A) Hand paths separated by target for non-dominant and dominant arms for a representative subject from each age group (old = top, young = bottom). Parametric measures of (B) hand path curvature, (C) absolute final position error, (D) variable error, across subjects (mean ± SE), for non-dominant (ND) and dominant (D) arms across subject groups.

Means of the individual dependent measures of task performance, including hand path curvature, absolute and variable final position error, peak tangentional velocity, and movement duration were analyzed using a 3-way mixed model analysis of variance (*ANOVA*), with arm (left = L or right = R) and age group (old = O or young = Y) as between-subject factors, and target (direction from horizontal axis: 50°, 90° and 130°) as the within-subject factor. Subjects were treated as a random factor. For all analyses, statistical significance was tested using an alpha value of 0.05. For post hoc analysis, our tests depended on whether the assumption of sphericity was violated, as tested by the Mauchly's test. If not, Tukey HSD (*Honestly Significant Difference*) was used for post hoc analysis. If assumption of sphericity was violated, then post hoc for within-subject factor (target) was corrected using the Greenhouse–Geisser for epsilon > 0.75, or Huynh–Feldt for epsilon < 0.75.

Typical hand paths from individual trials and final position distributions across all trials are shown for a representative participant from each group in Fig. 2A. Movements of both arms were generally well adapted to the direction of the targets for both groups. However, the younger group showed greater curvature of the non-

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dominant as compared with the dominant arm movements, such that the hand tended to curve lateral to the targets. The older group showed smaller differences in curvature between the left and right hand paths. Most interestingly, this reduction in lateralization was evidenced as straighter non-dominant hand paths, relative to the younger subjects, while dominant arm paths remained similar between the two groups. These findings were consistent across subjects, as shown in the graphs of average (±SE) hand path curvature (Fig. 2B). Our ANOVA showed a significant interaction between group and hand ($F_{1,40} = 4.86$; $p = .03$). Post hoc analysis revealed that left and right hand path curvatures were not significantly different for our elderly group ($p = 0.998$, Tukey HSD), while left paths were significantly more curved than right paths for our young subjects ($p = .027$, Tukey HSD).

Fig. 2A also shows the distribution of final positions for all the data from each representative subject from our groups. The ellipses reflect a 95% confidence interval. Our measures of absolute final position error (*FPE*), and variable error (*VE*) showed a significant group by arm interaction (*FPE*: $F_{1,40} = 4.95$; $p = .03$, *VE*: $F_{1,40} = 4.71$; $p = .04$). As evidenced in the group plots of absolute error (Fig. 2C), dominant arm movements were significantly more accurate than non-dominant arm movements for our younger subjects (0.027 m vs. 0.036 m; $p = .044$, Tukey HSD). However, there was no difference between arm groups in precision (Fig. 2D) for young subjects ($p = .24$, Tukey HSD). For older subjects, we found no significant differences between the arm groups for accuracy ($p = .97$, Tukey HSD) nor precision ($p = .66$, Tukey HSD). Interestingly, the elderly group showed more accurate (0.023 m vs. 0.031 m) and more precise (0.016 m vs. 0.023 m) movements, as reflected by a main effect of age group in our ANOVA for absolute ($F_{1,40} = 15.02$; $p = .0004$) and variable ($F_{1,40} = 21.45$; $p < .0001$) error, respectively. Our ANOVA also revealed a main effect of target on both absolute error ($F_{1.2,48.8} = 139.24$; $p < .0001$, Greenhouse–Geisser) and variable error ($F_{2,80} = 7.49$; $p = .001$). Furthermore, there was target × group interaction for variable error ($F_{2,80} = 3.85$; $p = .025$) but not for absolute error ($F_{1.2,48.8} = 2.07$; $p = .15$, Greenhouse–Geisser). Direction dependent variations in movement speed, direction, and accuracy have previously been detailed by Gordon et al. [14].

Previous studies have associated increased final position accuracy in elderly subjects with a reduction in speed [13]. However, in the current study, in which speed was an explicit requirement of the task, we saw no reductions in speed in our elderly subjects. Our ANOVA revealed a main effect of target ($F_{1.2,48.8} = 139.24$; $p < .0001$, Greenhouse–Geisser), such that movements toward the lateral direction were, on average, faster than movements toward the medial direction. There was no main effect for hand ($F_{1,40} = 0.66$; $p = .42$) and group ($F_{1,40} = 2.05$; $p = .16$), nor group × hand interaction ($F_{1,40} = 0.001$; $p = .97$). While there were no 2-way interactions with target ($p > .09$, Greenhouse–Geisser), there was a 3-way interaction target × group × hand ($F_{1.2,48.8} = 5.25$; $p = .02$, Greenhouse–Geisser).

As proposed by Schmidt [32], movement time rather than speed should be more predictive of movement accuracy. It is certainly plausible that movements with high peak velocities could be extended in the deceleration phase to allow for homing-in on the target. We, thus, quantified movement duration. Our ANOVA revealed group × hand ($F_{1,40} = 5.42$; $p = .025$) and group × target ($F_{1,40} = 5.42$; $p = .025$) interactions. There was a main effect of group ($F_{1,40} = 14.36$; $p = .0005$), with longer movement times for the young group (0.795 ± 0.021 s) relative to the older group (0.696 ± 0.018 s). There was also a main effect of target on movement time ($F_{2,80} = 53.03$; $p < .0001$), which is consistent with the work of Gordon et al. [14], indicating that movement times tend to be longer in directions associated with higher limb inertia.

Discussion: The purpose of this study was to examine whether aging affects asymmetries in motor coordination. Our previous research revealed robust asymmetries in interjoint coordination during multidirectional reaching movements in young adults [1,25]. These asymmetries were reflected by larger hand path curvatures in non-dominant arm movements during reaching made in the horizontal plane. We now compare multidirectional reaching in younger (20–40 years of age) and older (60–80 years of age) groups. Measures of hand path curvature and final position accuracy confirmed substantial asymmetries in young adults. However, in this study, the trajectories and accuracies of older adults were not asymmetric. This was reflected by straighter and more accurate movements of the non-dominant arm, rather than as a reduction in coordination and accuracy of the dominant arm.

Evidence from functional imaging studies has demonstrated that hemispheric asymmetry is reduced in older adults as compared to younger adults during cognitive tasks [6,7,15]. This hypothesis is based on the consistent finding of increased bilateral activation in older adults, primarily in prefrontal cortex (*PFC*), during a variety of memory encoding and retrieval tasks. The general finding that *PFC* activity during cognitive tasks is less lateralized in older adults as compared to younger adults has given rise to Cabeza's HAROLD model [4]. Most interestingly, Cabeza et al. [5] have provided evidence that this bilateral activation is compensatory in nature. They have shown that greater bilateral recruitment during memory tasks in older adults was associated with better task performance. Those subjects who performed poorly on memory tasks recruited asymmetrical patterns of neural activity, whereas those who performed well recruited bilateral patterns of activity. The results indicated that low-performing older subjects recruited a lateralized network similar to young adults, but used it inefficiently. In contrast, high-performing older adults counteracted age-related neural decline through recruitment of bilateral networks.

It is plausible that the reduced motor asymmetry of older adults, demonstrated in the current study, might correspond to similar compensatory recruitment to that demonstrated during cognitive tasks [5]. In support of this, Mattay et al. [19] showed increased ipsilateral activation patterns in older subjects, compared with young adults, during a simple unilateral button pressing task. Interestingly, this change in activation pattern occurred in the absence of decrements in task performance, suggesting that recruitment of bilateral networks may serve compensatory functions in motor tasks, as well as cognitive tasks. Chua et al. [8] showed that reaction times and movement durations remain asymmetrical in older adults, while Francis and Spirduso [11] extended the findings for movement duration for a variety of manual tasks. In our current study, we did not measure reaction time, and we controlled for movement speed. These findings indicate that when speed is matched between older and younger subjects, our older groups show a substantial reduction in asymmetry.

While our current findings focus on motor behavior asymmetries, recent studies from our laboratory, using stroke patients as lesion models, have allowed us to link our behavioral findings to neural asymmetries [16,29–31]. In brief, our dynamic dominance model suggests that each hemisphere should contribute a unique and specialized control process to each arm. A direct prediction of our hypothesis is that unilateral brain damage should produce predictable deficits in the arm that is ipsilateral to the lesion. Most importantly, these deficits should depend on the hemisphere that is damaged. Recent findings from our laboratory confirmed this prediction by characterizing ipsilesional arm deficits in single joint [31], and multijoint [16,29,30] movements. In short, right hemisphere lesions produced deficits in positional accuracy and precision for movements of the right, ipsilesional arm. Left hemisphere lesions produced deficits in torque specification and intersegmental coordination for movements of the left, ipsilesional arm. Thus, the motor asymmetries that we have

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characterized in young adults are reflected by asymmetries in the ipsilesional arms of patients with unilateral strokes. While these findings provide a link between motor asymmetries and potential hemispheric specializations, we do not have direct evidence that the reduced behavioral asymmetries reported in this study are related to changes in hemispheric activation.

Given that our previous findings have linked behavioral asymmetries in motor control with hemispheric specializations, our current findings of reduced asymmetry in older adults could arise from two mechanisms: First, it is plausible that as individuals age, contralateral circuits that control sensorimotor function become less efficient, requiring compensatory recruitment of ipsilateral circuits. This is consistent with the HAROLD model of Cabeza's [4], suggesting that behavior becomes more symmetric because neural recruitment becomes more symmetric. Alternatively, it is possible that when people gain more experience as they age, each hemisphere develops more complete control of each arm. For example, the non-dominant arm of elderly subjects in the current study could show improved coordination due to many more years of training, compared to the younger group. We are unable to distinguish between these alternative hypotheses with our current set of data. These behavioral findings are an important first step, but more conclusive evidence needs to await studies that incorporate neural imaging during movements in older adults.

Normal aging has been associated with deficits in coordination during goal-directed movements, such as those studied here [18,22,23]. We therefore expected that age-related reductions in lateralization might explain the genesis of age-related coordination deficits, rather than revealing an in improvement in coordination of non-dominant arm movements. One explanation for this apparent advantage of elderly for coordination of the non-dominant arm might be related to the findings of Cabeza et al. [5]. They proposed that increased recruitment of bilateral circuits, with aging, serves to compensate for loss of neural density in unilateral circuits. It is, therefore, plausible that compensatory recruitment of left hemisphere during left arm movement might improve coordination and accuracy for that arm. However, according to this idea, more complex tasks should tax this compensatory system, such that deficits in coordination become apparent. It should be stressed, however, that we do not have direct evidence that the reductions in motor asymmetry shown here are associated with changes in neural recruitment. As a result, this interpretation must be taken with caution.

In addition to the reduction in asymmetry in coordination, our data indicated a main effect of group for movement accuracy and precision, such that the elderly were slightly more accurate and more precise with both hands. This might be partially explained by our velocity requirements, which were determined based on preliminary data. The target velocity range between 0.5 and 0.8 m/s reflected the self-selected speed for our elderly group, while younger subjects tended to select faster speeds. Therefore, the younger subjects had to accommodate our speed requirements in this task, which resulted in even slower movements for our younger group than for our older group. We suggest that the higher attention requirement to adjust movement speed in our younger group may have resulted in slight reductions in accuracy, compared with the movements of the older group.

Overall, our findings indicate a reduction in motor asymmetry between our left and right arm groups of older subjects, as compared with our groups of younger subjects. This reduction in behavioral asymmetry is intriguing; given the fact that aging appears to be associated with a reduction in hemispheric asymmetry for cognitive tasks. However, whether these behavioral findings are related to systematic changes in neural recruitment during movement tasks cannot be determined by the current data, and must await further research.

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