Aging Effects on the Metabolic and Cognitive Energy Cost of Interlimb Coordination

William A. Sparrow,1 Suzanne Parker,1 Brendan Lay,2 and Michael Wengier1

1Deakin University, Melbourne, Australia.
2Pennsylvania State University, University Park.

Many everyday motor tasks have high metabolic energy demands, and some require extended practice to learn the required coordination between limbs. Eight older (73.1 ± 4.4 years) and 8 younger (23.3 ± 5.9) men practiced a high-energy two-hand coordination task with both 180° and 90° target relative phase. The older group showed greater performance error in both conditions, and performance at 90° was strongly attracted to antiphase coordination (180°). In a retention test one week following the acquisition trials, the older group had learned the 180° condition but did not learn the 90° condition. Metabolic energy cost was not different between groups, but the older men showed higher heart rate and both conditions imposed greater cognitive demands as revealed in auditory probe reaction time. Older adults’ motor learning may be inhibited by elevated heart rate at the same oxygen cost, increased cognitive cost, and an attraction toward more established low-energy in-phase or antiphase coordination.

PERFORMANCE across a range of everyday motor tasks is reduced as a consequence of declines in cognitive and neuromuscular processes with aging (1–5). One characteristic of many day-to-day motor skills, such as walking or vigorous household activities, is that compared to most laboratory tasks they have high metabolic energy demands. Such motor skills impose physical work demands but also engender subjective feelings of mental effort or “cognitive work,” particularly when the task is novel or unusually challenging. In the experiment reported here we used a high-energy coordination task to investigate both the metabolic and “cognitive energy” costs of motor performance and learning in young and older males.

In performing and learning many motor skills, a fundamental challenge is establishing the required coordination, such that the timing of two or more limb movements is optimized relative to the task goal. The theoretical position on interlimb coordination adopted here is from dynamic pattern theory or “coordination dynamics” (6). From this perspective coordination between either different limbs or between segments within a limb can be measured by calculating relative phase, the angular difference between the coordinated elements (7). Across a variety of motor tasks there are preferred coordination patterns that, theoretically, serve as dynamically stable “attractor states” in terms of variability in relative phase (8). It is well established in the bimanual coordination literature that in-phase (moving together in time) and antiphase (half a cycle out of phase) constitute stable, attractive, coordination tendencies and any other interlimb timing functions are only established following practice (7–9). In other words, motor learning is driven by the natural tendency of dynamic systems, such as humans in motion, to achieve stable low-energy configurations usually associated with either in-phase or antiphase coordination. Motor skills considered “difficult” to learn are, therefore, those requiring interlimb phasing between in-phase (0°) and antiphase (180°), such as 90° relative phase. It would also be predicted that such patterns would have higher cognitive and metabolic energy demands than in-phase or antiphase movements.

To manipulate interlimb coordination while also imposing high metabolic energy demands, in this experiment two arm-and-hand ergometers were positioned side-by-side allowing the inside handle of each ergometer to be moved independently. Two metronome-paced conditions against resistance were practiced by young and older participants. In one condition, the target relative phase between the hands was 180° (antiphase); in the second, 90° relative phase such that one hand followed the other by one quarter of a cycle. It was expected that in both groups less absolute error and lower cycle-to-cycle variability would be found in the antiphase pattern compared with the 90° relative phase (10). Furthermore, on the basis of previous work in our laboratory (11), it was anticipated that older adults’ performance in the antiphase condition would be similar to that of younger adults, whereas the older adults would show considerably less capacity to perform the 90° phase pattern.

The attention demand of motor tasks has been determined by measuring the increase in reaction time from a baseline condition without performing the primary motor task to a “dual-task” condition when performing both the reaction time task and the motor task simultaneously (12). Previous work on interlimb coordination (13,14) has already indicated that probe reaction time is faster when performing the more stable in-phase coordination than the antiphase pattern. Although aging effects on the attentional cost of interlimb coordination have not previously been investigated, it has been shown that reaction time declines with age and that age-related slowing is increasingly apparent when greater movement task complexity extends attentional resources (1,15–18). In a gait experiment, for example, it was found that
when walking in the laboratory older participants’ reaction time to both a visual and a combined auditory/visual stimulus was significantly longer than that of younger adults, indicating that the attention cost of unconstrained walking was higher in the older group (19). When in a second condition participants were required to also position one foot within a narrow target area on the floor, reaction times to the probes were considerably longer for older adults, such that the constraint on foot placement increased the attentional cost of walking.

The first research question addressed here was whether, for older individuals, performing the same motor task is both more difficult in terms of absolute error relative to the task goal and more costly in both metabolic energy and cognitive resources than it is for younger adults. In addition, it was of interest to determine the effect of task difficulty on motor performance by manipulating the relative phase of interlimb coordination.

With evidence that physical and cognitive declines with age are compounded by inactivity, older adults are increasingly being encouraged to take up pursuits with sufficiently high cardiovascular demands to engender health benefits (20). Although there has been research interest in chronological age effects on performance across a range of motor tasks, few studies have considered aging effects on motor skill learning. If, for example, improvements in performance are observed with practice do they reflect “relatively permanent” changes in behavior? It has been argued in the motor learning literature that the permanence of performance should be revealed in a later, no-feedback retention condition administered following the initial acquisition or training phase of the experiment (21,22). There is already evidence that older adults have the capacity to retain motor performance gained in the acquisition phase. In a movement-timing experiment, when augmented feedback was removed in a later retention test, although the younger group was more accurate the older participants did learn the task (23). In a similar study (24), in a no-feedback retention test, older participants in two of three feedback conditions retained the gains made in the acquisition phase.

A second research question was, therefore, whether aging would affect the capacity to learn the two interlimb coordination task conditions with extended practice. With evidence that older adults can retain motor capacities as demonstrated on a later retention test, it was hypothesized that older adults would demonstrate motor skill learning. The experimental design therefore incorporated first an acquisition phase comprising practice at the task for three sessions over three weeks, followed one week later by a no-feedback (without metronome pacing) retention trial to show whether participants in either group had retained any capacities acquired in the earlier acquisition trials.

Methods

Eight healthy older men (mean 73.1 ± 4.4 years, height 174.8 ± 5.4 cm, weight 87 ± 14.6 kg) and 8 healthy young males (mean 23.3 ± 5.9 years, height 182.1 ± 11.6 cm, weight 82.6 ± 15.9 kg) volunteered to participate. The Deakin University Research Ethics Committee approved the experimental methods and procedures for informed consent. All participants completed a medical questionnaire to confirm the absence of musculoskeletal and neurological conditions and any other medical considerations that might have suggested exclusion. Older participants were healthy, living independently in the community, and physically active, in reporting via a questionnaire that they walked for recreation and were involved in vigorous leisure activities.

The ergometer apparatus comprised two Monark 881 hand cycle ergometers (Monark Exercise AB, Varberg, Sweden) placed side by side and secured to a wooden desk such that the handles of each machine could be moved independently. Participants operated the machine while seated behind the desk on a standard office chair with back support. Prior to testing, the ergometers were calibrated to a workload of 22 W at 40 cycles/min. Comparison of resting heart rate to working heart rate indicated that for older participants the task elicited a 37% (antiphase) to 39% (90° phase) increase in metabolic energy cost above resting and in young participants a 28% (antiphase) to 40% (90° phase) increase.

To measure relative phase between the hands 3-D coordinates were sampled continuously (100 Hz) from one Infra-Red Emitting Diode (IRED) of an Optotrak (Northern Digital Inc., Waterloo, Ontario, Canada) movement analysis system secured to the back of a left and right glove worn during data collection. The raw 3-D data were low-pass filtered with a cutoff frequency of 9 Hz with the Butterworth filter provided with the Optotrak data analysis package. Metronome tones were used to maintain cycle rate at 40 rpm and also to specify the relative phase of the handles. In both conditions (180° phase and 90° phase) the metronome emitted a different tone for each handle. Participants were instructed to synchronize the motion of each hand such that it reached a marker on the ergometer casing at the same time as the metronome tone.

Oxygen consumption and carbon dioxide production were measured continuously with an expired air analyzer with dedicated hardware and software (Medgraphics Corporation, St. Paul, MN). The analyzer was calibrated prior to every trial with gases of known concentration. An expired air mouthpiece and heart rate monitor were attached to the participant prior to each test. Heart rate was sampled every 15 seconds with a Polar Vantage (Polar Electro Oy, Kempele, Finland) heart rate monitor strapped around the chest, the reading was the mean heart rate for the preceding 15-second sample period. The reaction time apparatus comprised a response button located on the right handle beneath the thumb. The response button was attached to a computer via a light flexible cable, and the auditory stimulus was the built-in computer chime activated by using in-house developed software. The stimulus was initiated from the keyboard, and the computer also stored the reaction time data.

Prior to the first session it was demonstrated how the metronome specified the target relative phase of the left and right hands in the two conditions (180° phase and 90° phase). It was strongly emphasized that the goal was to maintain the target relative phase throughout the cycle, not only when the handles passed the markers on the ergometer casing. For the no-cycling baseline reaction time task, participants were instructed to hold the right ergometer handle and respond to the auditory probe by pressing the button as fast as possible.
RESULTS

whether either group had learned the task as revealed by retention trial within each participant group to determine any differences between the first acquisition trial and the transition phase. Dependent (correlated) significant effects on the dependent variables in the acquisition (Trial) repeated measures analysis of variance to determine for each trial were entered into a 2 (Age) within a trial. The absolute relative phase data in Figure 1 can be interpreted further by examining the magnitude (absolute error), direction (constant error), and variability (variable error) of the deviation from target relative phase, as shown in Figure 2. The absolute error results confirmed that in acquisition older adults were consistently far from the target coordination and as practice progressed they shifted even further from 90° phase. By the last acquisition trial the older group performed the 90° phase task with a relative phase of 143° compared with 132° at the beginning of practice; they produced similar relative phasing in both task conditions. In contrast, in the 90° phase condition the young participants initially performed 121° after which they were consistently close to the target. On the final acquisition trial, however, their performance shifted direction, with mean relative phase of 68°; when constant error for individual subjects was plotted, this shift was seen in 7 of the 8 young participants. The younger group showed consistently accurate performance in the 180° phase condition, whereas the older participants began at 131° and improved to 148° by the end of acquisition. Figure 1 also reveals that task performance in both conditions was retained with the older group improving performance relative to the final acquisition trial (a “reminiscence” effect).

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There was a significant condition effect on constant error

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Table 1. Experimental Procedure for Acquisition and Retention Sessions

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<th>Trial 1 (180° or 90° phase)</th>
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Note: The first trial was preceded by 4 minutes of baseline reaction time (RT). The protocol then comprised 2 minutes of resting oxygen consumption (O₂) and heart rate collection (HR), followed by 4 minutes of practice with RT probes while O₂, HR, and relative phase data were collected continuously.

They were asked to do the same during the cycling task while also maintaining target relative phase and to divide their attention equally between the cycling task and the reaction time probe. The baseline reaction time was subtracted from the cycling reaction time to reflect the attention demand of the primary cycling task in “difference reaction time.”

Table 1 shows the protocol for each of six practice sessions in which there were two trials at the same condition, either 180° or 90° relative phase, a total of twelve trials. One week following these trials there was a retention session of only one trial in each condition. The presentation order for each condition was counterbalanced across trials and between participants. The baseline and cycling reaction time probes were both presented six times each minute by using two schedules designed to prevent stimulus anticipation. On the even numbered sessions at 12, 21, 32, 42, 50, and 58 seconds and on the odd numbered sessions at 10, 18, 28, 38, 43, and 55 seconds.

Interlimb coordination was measured by first calculating point relative phase based on the time difference between the two handles (left and right hands) passing a specified position relative to the apparatus. The absolute time difference was then divided by the right handle’s cycle time and multiplied by 360 to express the between-hands time difference in degrees. Subsequently the absolute error of relative phase was calculated as the mean absolute deviation between the performed relative phase and the target relative phase (either 90° or 180°). The direction of error was revealed by constant error calculated as for absolute error except retaining the sign of the deviation scores. To quantify cycle-to-cycle variability in relative phase, the variable error was calculated as the standard deviation of absolute error for all observations within a trial.

Absolute error, constant error, and variable error of relative phase, oxygen consumption, heart rate, and reaction time for each trial were entered into a 2 (Age) × 2 (Condition) × 6 (Trial) repeated measures analysis of variance to determine significant effects on the dependent variables in the acquisition phase. Dependent (correlated) t tests were used to show any differences between the first acquisition trial and the retention trial within each participant group to determine whether either group had learned the task as revealed by significantly improved performance in retention.

RESULTS

Relative Phase

Figure 1 shows the performed relative phase in the two conditions across trials. In the 90° phase condition the older adults were consistently far from the target coordination and as practice progressed they shifted even further from 90° phase. By the last acquisition trial the older group performed the 90° phase task with a relative phase of 143° compared with 132° at the beginning of practice; they produced similar relative phasing in both task conditions. In contrast, in the 90° phase condition the young participants initially performed 121° after which they were consistently close to the target. On the final acquisition trial, however, their performance shifted direction, with mean relative phase of 68°; when constant error for individual subjects was plotted, this shift was seen in 7 of the 8 young participants. The younger group showed consistently accurate performance in the 180° phase condition, whereas the older participants began at 131° and improved to 148° by the end of acquisition. Figure 1 also reveals that task performance in both conditions was retained with the older group improving performance relative to the final acquisition trial (a “reminiscence” effect).

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There was a significant condition effect on constant error
in acquisition ($F_{1,14} = 29.63, p = .001$) due to higher constant error in the older group for the 90° phase. There were also significant interactions for constant error, but these are not easily interpreted due to the effects of the sign of the constant error score, and are not reported. Most important, as indicated in Figure 2B, is that older adults produced larger constant error in both conditions. As seen in Figure 2C, variable error was higher for the older group ($F_{1,14} = 13.10, p = .003$), but this was the only significant effect on variable error.

To illustrate age and practice effects on learning the motor task, the retention trial and first acquisition trial absolute error and variable error are graphed in Figure 3. For absolute error one $t$ test comparison reached significance, showing that the older adults reduced error in retention in the 180° phase condition ($t(7) = 2.43, p = .04$). The absolute error results for the young group showed that, although they tended to have less error in retention, the difference between the acquisition trial 1 means and the retention was not significant. The young participants did, however, learn to perform more consistently in both conditions as shown in significantly lower variable error in retention than on the first acquisition trial, $t(7) = 4.59, p = .002$ (180° phase) and $t(7) = 3.22, p = .01$ (90°-phase).

In summary, the relative phase data showed that the older group performed with greater error in both conditions and they learned the 180°-phase pattern but not 90° phase. The younger participants performed both tasks well following one practice trial but did not, by the present criteria, learn either task condition. The young individuals learned to reduce cycle-to-cycle variability in both conditions, whereas the older group did not.

**Metabolic Variables**

Figure 4 presents oxygen consumption and heart rate for acquisition and retention. There was no age effect on oxygen consumption in acquisition but, despite that, older adults had significantly higher heart rates ($F_{1,14} = 5.41, p = .03$). There was a significant practice effect on both oxygen consumption ($F_{5,10} = 9.35, p = .002$) and heart rate ($F_{5,10} = 4.26, p = .02$), confirming an overall decrease in metabolic cost across trials. It is, however, important to note that the significant decline in both heart rate and oxygen consumption was due primarily to the decrease shown in the young group; the Practice × Age interactions that would have confirmed this did not, however, achieve significance ($F_{5,10} = 3.05, p = .06$ for heart rate; $F_{5,10} = 2.32, p = .12$ for oxygen consumption). There were no other significant results for the metabolic variables in acquisition.

As illustrated in Figure 5, younger adults demonstrated...
significantly lower oxygen cost in both 180° phase retention ($t[7] = 3.90, p = .006$) and 90° phase ($t[7] = 2.79, p = .02$). The younger group also learned to reduce heart rate in the 90° phase task ($t[7] = 3.18, p = .01$), but the older men did not learn to perform either condition with lower oxygen consumption or heart rate.

**Reaction Time**

Although the baseline reaction time data in Figure 6 did not reveal an age-group difference in acquisition, the result approached significance ($F_{1,14} = 4.23, p = .059$). The most important result from the reaction time analysis was age effects on the attentional cost of performance revealed in older adults’ significantly longer cycling reaction time ($F_{1,14} = 23.05, p = .001$) and difference reaction time in acquisition ($F_{1,14} = 15.62, p = .001$) for both conditions (180° phase: older = 156 ms, younger = 75 ms; 90° phase: older = 193 ms, younger = 90 ms). Significant condition effects were also obtained for cycling reaction time and difference reaction time (respectively, $F_{1,14} = 4.68, p = .04$; $F_{1,14} = 13.49, p = .003$) due to longer reaction time in 90° phase cycling. Although there was a consistent trend of decreased cycling reaction time and difference reaction time in young adults in both conditions, the analysis of variance produced no practice effects on baseline, cycling, or difference reaction time, indicating that the attentional cost of the task was unaffected by practice in acquisition. There were no interaction effects on any of the three reaction time variables.

Figure 5 shows the acquisition trial 1 and retention means for difference reaction time only, reflecting the attentional cost of primary task performance. The young participants significantly reduced difference reaction time from the first acquisition trial to retention only in 90° phase coordination ($t[7] = 2.60, p = .03$), whereas the older group reduced cognitive cost in 180° phase ($t[7] = 3.45, p = .01$).

**DISCUSSION**

The first question addressed here was whether aging influences older individuals’ capacity to perform a high-
energy coordination task. The major finding concerning aging and motor performance was that, during the acquisition trials with augmented feedback from the metronome, older adults performed both relative phase conditions with less interlimb timing accuracy than did young adults, supporting the hypothesis that aging adversely influences the capacity to perform interlimb coordination tasks. A striking finding from the relative phase acquisition data was with respect to older adults’ performance in the 90° phase condition. Not only were they considerably less accurate than the young controls, but they did not improve with practice, deviating progressively further from the target 90°. Older adults, therefore, demonstrated difficulty in achieving the 90° relative timing, in the same way that previous research has shown young participants initially being drawn toward either antiphase or in-phase coordination (7–9,25). In experiments by Zanone and Kelso, however, young participants improved their performance in the 90° phase condition that eventually became an attractive state. In contrast, the older groups’ data in the present experiment support the ‘inhibition hypothesis’ (26) that proposes that older individuals have a reduced capacity to inhibit preferred coordination tendencies to learn more complex coordination patterns such as 90° relative phase. Difficulties in overcoming preferred coordination modes in older adults have been attributed to age-related declines in inhibitory control processes that would normally serve to assist in “decoupling” the preferred tendency in favor of the to-be-learned pattern (26,27).

Although there was no significant reduction in absolute relative phase error with practice during the acquisition trials, there was a decreasing trend for older adults in the antiphase condition, suggesting some capacity to improve performance on a relatively stable coordination pattern. Lack of significant improvement in both conditions by younger adults may have been due to the task being established early in practice, further highlighting their capacity to quickly master both relative phase conditions. In summary, it is proposed that a combination of cognitive declines (inhibition) in conjunction with the dynamic stability of antiphase timing demanding less metabolic and cognitive energy caused the older group to be more attracted toward antiphase coordination.

The second research question was whether older adults would learn the task with extended practice. Following acquisition, a single retention trial was undertaken with augmented feedback from the metronome withdrawn, and learning was inferred if retention performance was significantly lower than on the first acquisition trial. The relative phase analysis indicated that, when absolute error on the first acquisition trial was compared with that on the retention trial, the older adults learned to perform the 180° phase condition but not the 90° phase. This result is consistent with the above discussion that older adults’ absolute error increased in 90° phase due to the pull toward antiphase and that younger individuals, having established the task early, had little scope for improvement. Although the younger group did not learn to reduce absolute error, their variable error data indicated that they learned to perform both conditions with less variability whereas the older group did not, suggesting less capacity to modify relative timing from cycle to cycle to approximate the target relative phase.

Oxygen consumption did not reveal an age effect in acquisition, indicating that for this task any age-related declines in physiological processes (28,29) did not inhibit older adults’ capacity to perform economically. It was, however, found that heart rate was significantly higher for the older group. In previous work with similar tasks, high heart rates have been associated with increased ratings of perceived exertion, measured using Borg Scales (30,31). Older adults may, therefore, experience elevated sensations of perceived exertion when performing motor tasks even when the metabolic energy cost is relatively low. In summary, we hypothesize that novel high-energy motor tasks may be avoided by older adults due to negative sensations of exertion associated with elevated heart rate.

The significant practice effect on oxygen consumption confirmed previous findings of reduced metabolic energy cost with practice at high-energy coordination tasks (32–35). As the in-phase and antiphase conditions constitute stable low energy attractors of the coordination dynamics, the finding of reduced metabolic energy cost with practice in both groups reflects the shift we observed toward these two patterns. Further, where absolute error and constant error
were greatest for older adults in 90° phase (trials 3–4) the oxygen consumption decreased, suggesting that performing antiphase in favor of 90° phase was associated with lower energy cost. It was interesting, therefore, that the propensity to minimize metabolic energy cost by performing closer to in-phase or antiphase tended to override the imposed external pacing designed to engender the higher energy-demanding phase relation of 90°. Most importantly the results suggested, therefore, that to reduce the metabolic demands of the task, both groups were attracted toward the low energy in-phase and antiphase patterns. In learning new skills, older adults may tend to avoid unstable high-energy coordination patterns even if they are the desired or target patterns for the novel task. This conclusion is reinforced by the observation that, for the oxygen consumption data, comparison of the first acquisition trial with the retention trial showed that the young individuals learned to become more economical in both conditions, whereas the older group did not.

Significantly longer cycling reaction time and difference reaction time in both conditions showed that motor performance was more attention demanding for older participants. The high attentional cost of 90° relative phase in older adults may have been due to the cognitive resources required to resist the “attractive” antiphase pattern. In baseline there was no significant difference in reaction time between young and older individuals, confirming earlier findings (19) of no age effect on baseline reaction time in similar participants. In the present study the difference between age-group baseline reaction time means approached significance (p = .059), and we conclude that, although reaction time appears to slow with age across a range of tasks (16,18), healthy, physically active males in the age range studied here can maintain single-task reaction time at levels approximating young controls.

The present study highlights, however, that with increased task complexity, age differences in reaction time become apparent and that age-related declines in cognition may inhibit older adults’ performance when it is necessary to divide attention across multiple tasks. It has been hypothesized that performance decrements in dual-task conditions in older adults are due to reduced information processing speed (19,36,37). It has been suggested, furthermore, that reduced processing speed engenders slower attentional switching between two or more tasks (37). In future work it may be useful to determine whether age-related performance deficits in dual task situations are due to attentional switching. Alternatively, as implied from the findings presented here, increased cognitive cost of the primary task in older adults may be confirmed as causing the longer reaction time to the secondary task.

Contrary to expectation there was no practice-related decline in cognitive cost as reflected in difference reaction time in the acquisition phase. In the younger group this result is consistent with the earlier discussion of the target coordination being established early in practice in both conditions. For older adults the finding of no decline in difference reaction time in the antiphase task is, again, expected given the absence of significant improvement in the accuracy of that condition. When, however, the retention performance was examined for difference reaction time, younger participants learned to reduce the task demands in the 90° phase, and older participants in the 180° phase. The finding that older adults reduced the cognitive demands of the antiphase task supports the earlier conclusion that they also reduced absolute error in the retention condition. The young adults, in contrast to the older, were successful in learning to reduce the cognitive demands of 90° phase performance but, once again, due to performing well early in practice they did not, by the present criteria, learn the task.

Many everyday tasks and recreational activities require the capacity to perform and learn specific patterns of interlimb coordination. The findings reported here show how aging influences the performance and learning of a metabolically and cognitively demanding coordination task. Because older adults are increasingly encouraged to adopt high-energy recreational activities for health benefits, such research is important. It is proposed that the performance and learning of high energy coordination tasks in older adults may be adversely influenced by an attraction toward in-phase or antiphase coordination. In this experiment the intrinsically attractive 180° phase timing was practiced at the same time as 90° phase timing, and as the antiphase pattern further strengthened it may have nullified the older adults’ attempts to achieve 90° phase timing.

A possible explanation for the attraction toward antiphase coordination is that, although imposing the same metabolic energy demand as for younger individuals, the 90° phase pattern was associated with both higher attention demands and elevated heart rate leading, possibly, to greater perceived exertion. To minimize the metabolic and cognitive cost of learning new motor skills, older individuals may fail to inhibit preferred, stable, low-energy movement patterns. When older adults were shown to have learned the task by comparing initial performance with the retention trial age-group differences were preserved in retention. Within the limits of the number of practice sessions used in this experiment, age differences in the energetic cost and coordination accuracy were, therefore, maintained when learning a novel high-energy motor task.

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Address correspondence to William A. Sparrow, PhD, School of Exercise and Nutrition Sciences, Deakin University, 221 Burwood Hwy., Burwood 3125, Australia. E-mail: sparrow@deakin.edu.au

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