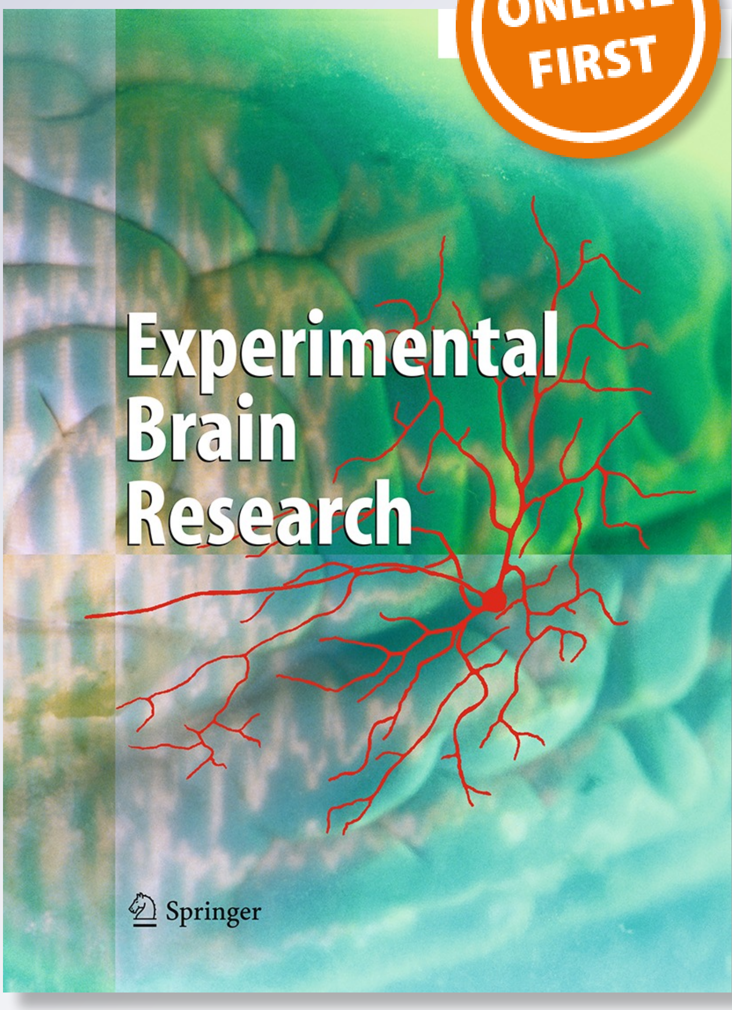
Slow and steady is not as easy as it sounds: interlimb coordination at slow speed is associated with elevated attentional demand especially in older adults

Hakuei Fujiyama, Mark R. Hinder, Mike I. Garry & Jeffery J. Summers

Experimental Brain Research

ISSN 0014-4819

Exp Brain Res
DOI 10.1007/s00221-013-3511-7



Exp Brain Res
DOI 10.1007/s00221-013-3511-7

RESEARCH ARTICLE

Slow and steady is not as easy as it sounds: interlimb coordination at slow speed is associated with elevated attentional demand especially in older adults

Hakuei Fujiyama · Mark R. Hinder · Mike I. Garry · Jeffery J. Summers

Received: 16 January 2013 / Accepted: 3 April 2013

Abstract The present study investigated age-related changes in the attentional demands associated with interlimb coordination involving upper and lower limbs performed at three different movement frequencies. Younger and older adults performed rhythmical, 180° out-of-phase flexion–extension movements of the knee and elbow with either ipsilateral (right arm, right leg) or contralateral (right arm, left leg) limbs at 20, 60, and 100 % of each individual's maximum movement frequency. A concurrent vocal reaction time task (dual task) was used to assess attentional load. There were two major findings: (1) The attentional cost associated with undertaking the required coordination patterns was greatest at the slowest movement frequency, and this additional attentional load was most pronounced for older adults; (2) the manipulation of movement frequency had a distinct effect on the coordination performance: moving at the fastest frequency degraded the accuracy and stability of coordination, while moving at the slowest movement frequency led to increased temporal variability, particularly in older adults. Coordination performance at slowest movement frequency required the greatest cognitive demand in older adults relative to other movement frequencies, suggesting that going 'slow and steady' is not necessarily less attentionally demanding for older adults.

Keywords Interlimb coordination · Attention · Dual-task · Slow movement · Aging

H. Fujiyama (✉) · M. R. Hinder · M. I. Garry · J. J. Summers
Human Motor Control Laboratory, School of Psychology, University of Tasmania, Hobart, TAS 7001, Australia
e-mail: Hakuei.Fujiyama@utas.edu.au

Introduction

Maintenance of motor function, especially the coordination of upper and lower limbs, is a major concern for older adults since it is intrinsic to many daily activities such as walking and driving a car. Indeed, compromised coordination increases the risk of falls (de Rekeneire et al. 2003) and decreases functional independence (Spirduso 1995). With respect to bimanual coordination, performance is more stable and accurate, when the limbs are moving in a mirror-symmetrical manner (in phase) in which homologous muscles are simultaneously activated, than when the upper limbs move in a non-symmetrical manner (antiphase). For coordinating upper and lower limbs, coordination stability and accuracy are higher when the limbs are moved in the same direction (isodirectional) in external space compared to when they move in opposite directions (non-isodirectional) (Baldissera et al. 1982; Hiraga et al. 2004, 2005; Kelso and Jeka 1992; Meesen et al. 2006; Serrien and Swinnen 1997; Swinnen 2002). Another important factor impacting on the performance of interlimb coordination is the cycling frequency of the limbs (Baldissera et al. 1982, 1991; Carson et al. 1995). With increasing movement frequency, an involuntary transition (phase transition) at a critical frequency (CF) can be often observed from the anti-phase pattern for bimanual coordination and non-isodirectional pattern for upper- and lower-limbs coordination to the more stable in phase and isodirectional patterns. The effect of aging on interlimb coordination appears to be highly dependent on movement frequency: it has been consistently shown that older adults can achieve a similar performance level (as judged by accuracy and stability of movements) as younger adults at slow frequencies, but clear age-related degradation of performance is evident at

Published online: 17 April 2013

fast movement frequencies (e.g., Fujiyama et al. 2010; Lee et al. 2002).

It has been argued that age-related decline in motor performance, including interlimb coordination, is the manifestation of the overall slowing in cognitive, motor, neural, and perceptual processes that occurs with advancing age (e.g., Hunter et al. 2001; Morgan et al. 1994; Salthouse 1991, 1996). Several hypotheses have been put forward to explain the age-related slowing. One view suggests that increased noise in neural networks of motor and perceptual systems (Li and Sikstrom 2002; Welford 1988) results in older adults making slower movements in order to achieve or maintain successful performance (Walker et al. 1996). An alternative explanation proposes decreased complexity in the dynamics of physiologic systems with age (i.e., 'loss of complexity hypothesis'—Goldberger et al. 2002; Newell et al. 2006). In order to perform cognitive or motor tasks, physiological functions are required to integrate the complex networks of neural control systems, feedback loops, and other regulatory mechanisms (Lipsitz 2004). With advancing age, the complexity of a physiological system declines due to a reduction in the number of individual physiological structural components or reduced efficiency in functional connectivity between these components (Vaillancourt and Newell 2002). These changes may contribute to motor slowing in older adults by increasing the time to process information, integrate the perceptual and motor aspects of the information, and generate motor responses. Regardless of the etiology of motor slowing, there is a general consensus that older adults have difficulty performing a motor task at faster speeds, but not at slower speeds.

It has been shown that increasing the oscillatory frequency of a motor pattern reduces its stability and thereby increases the attentional load needed to maintain the pattern (Temprado et al. 2001). Studies investigating age-related changes in interlimb coordination at different movement frequencies have also reported that older adults show performance decline at relatively higher movement frequencies ($\geq$1.5 Hz), but not at moderate movement frequencies ($\leq$1.0 Hz) (Greene and Williams 1996; Heuninckx et al. 2004; Lee et al. 2002). For example, Lee et al. (2002) found that at 1 Hz, there were no age differences in bimanual coordination performance (using both upper limbs) and attentional measures (a serial counting task) irrespective of coordination patterns, that is, mirror symmetrical or asymmetrical, or whether the coordination task was performed on its own or under dual-task conditions. It has been suggested that the maintenance of interlimb coordination patterns at slower movement speeds with advancing age may be because they are more automatically processed than movements conducted at faster speeds (Swinnen 2002).

A recent study from Krampe et al. (2010), in contrast, reported that older adults required *greater* levels of attention and working memory to execute a rhythmic movement (unimanual finger tap) at slow movement speeds than at faster movement speeds. Specifically, the authors used a dual-task paradigm, which required participants to perform a unimanual finger tapping task at either short (550 ms) or long (2,100 ms) inter-tap intervals alone, or while concurrently undertaking an nBack task. While tapping performance in the single-task condition was not different between short and long intervals for either younger or older adults, under the dual-task conditions performance at the longer tapping interval (i.e., slower tapping frequency) degraded significantly relative to performance at the shorter interval (faster tapping frequency), particularly in older adults. These results suggest that a fast tapping rhythm can be undertaken by recruiting low-level (automatic) timing mechanisms with minimal attentional requirements, which appear to be unaffected by normal aging. In contrast, higher-level timing mechanisms (with a substantial degree of attentional input) are required to control a slower tapping rhythm; these mechanisms appear to be compromised with advancing age (e.g., Commodari and Guarnera 2008; Zacks et al. 2000). While this study indicates that slow movements may not necessarily be easier, the results cannot be assumed to generalize to more complex tasks, such as interlimb coordination.

While providing substantial insights into the role of attention in interlimb coordination, existing studies (Greene and Williams 1996; Heuninckx et al. 2004; Lee et al. 2002) have neglected to study the effect of very slow movement frequencies (i.e., significantly below the natural or preferred frequency at which someone would choose to undertake a particular task) on attentional cost during an interlimb coordination task in older adults. It is, therefore, not known whether interlimb coordination performed at very slow movement frequency is also more cognitively demanding for older adults than younger adults. Here, we investigated the performance of upper- and lower-limbs interlimb coordination at very low, moderate, and very fast movement frequencies in younger and older adults with a dual-task paradigm to assess attentional cost required for each movement frequency. It was hypothesized that the attentional cost would be higher for older adults than younger adults at the slow movement frequency due to the involvement of high-level timing processes that may be compromised with advancing age. There is evidence that although, for interlimb coordination requiring such timing processes, older adults can produce stable and accurate coordination performance, the variability between movement cycle durations (temporal variability) significantly increased relative to young adults (Summers et al. 2010). It was predicted, therefore, that the reduced efficacy of high-level timing processes in older age would be reflected by increased temporal variability in movements produced at a very slow movement frequency relative to movements produced at faster frequencies or by younger adults. Furthermore, age-related interlimb coordination deficits are often evident when non-isodirectional patterns are performed at maximum speed (e.g., Lee et al. 2002). It was, therefore, expected that age-related differences in coordination performance would also be observed at frequencies close to an individual's predetermined maximal movement frequency due to the increased attentional demands of preventing a phase transition to the more stable in phase coordination (Temprado et al. 2001).

Methods

Participants

Twenty-four healthy self-reported right-handed volunteers participated in the study, including 12 older adults (6 males, 6 females, $M_{age} = 67.1$ years; $Range_{age} = 60–75$ years) and 12 younger adults (6 males, 6 females, $M_{age} = 21.3$ years; $Range_{age} = 18–26$ years). The mini-mental state examination (Dick et al. 1984) was used to screen for cognitive deficits in the sample of older adults. A score of 23 or less is 'suggestive of cognitive impairment' (Dick et al. 1984). The average score of the older participants in this study was $M = 28.82$ (SD = 1.32 range = 26–30). All participants were free of any neurological defects, symptomatic cardiovascular disease, diabetes, hypertension, or history of severe head injury. Written informed consent was given prior to participation in the study. Ethics approval for the study was obtained from the University of Tasmania Ethics Committee.

Apparatus

Participants were seated in a custom-made chair consisting of a steel frame with a wooden back support and padded seat. The chair had four aluminum levers against which participants' arms and legs were attached using elastic bandages, which allowed independent flexion and extension motion of the forearms and lower legs in the sagittal plane. Height adjustable footrests attached to the leg levers were used to support the lower legs. The position of each lever was fully adjustable, such that the axis of rotation was aligned coaxially with the elbow or knee joint. Limb position data were obtained using potentiometers coaxial with each lever's axis of rotation. The voltage output from the potentiometers was sampled at 500 Hz using a 12-bit A/D system and was recorded on a computer hard drive for analysis off-line. The raw position data were low-pass filtered with a cutoff frequency of 50 Hz using a dual-pass Butterworth filter. Custom written software was used to derive and calculate the kinematics and spatiotemporal coordination measures.

A computer placed approximately 1 m in front of participants (at eye level) was used to present a visual metronome which was projected on the computer screen as a 10-cm-diameter circle flashing (at the desired movement frequency) with a duration of 100 ms. Auditory stimuli (1,400 Hz computer-generated signals of 50 ms duration) presented via loudspeakers were used to investigate probe reaction time. Responses to these stimuli were recorded through a microphone attached to headphones (Verbatim, Charlotte, USA) on the participant's head. The vocal signal was fed into an electrically operated switch device ('voice activated relay,' Bogen, Ramsey, USA) and transformed into a digital output signal. The sensitivity was adjusted for individual participants to ensure accurate detection of response onset.

Procedure

Participants were instructed to complete one movement cycle in time with the visual metronome. The task required concurrent cyclical flexion and extension movements at the knee and elbow with a 1:1 movement frequency ratio. The starting positions of the limbs were approximately 90° flexion for the elbow and knee. One complete movement cycle (i.e., from flexion to extension and back to flexion) was performed between consecutive visual stimuli. No specific movement amplitude was required at either limb, and participants were instructed to move their limbs at their preferred amplitude. This was to avoid imposing an additional attentional load on participants, particularly older adults (Fujiyama et al. 2009). There were two movement conditions, requiring the cyclical coordination of either contralateral limbs (right arm and left leg) or ipsilateral limbs (right arm and right leg). Both movement conditions involved non-isodirectional movements, that is, the arm and leg moved in opposite directions (Fig. 1a). The limbs not involved in a required task remained at rest.

Prior to the experimental session, critical frequencies (CFs) for each limb combination were determined for each participant in a series of metronome-paced trials in which frequency was increased 0.25 Hz every 8 s from 1 Hz. The critical frequency was the rate at which participants were no longer able to maintain the required coordination pattern, that is, showing signs of imminent phase transition from approximately 180° (non-isodirectional mode) to 0° (isodirectional mode) or participants failed to maintain the required frequency.

To ensure that compatible levels of task difficulty were used for both younger and older adults, during the experimental trials, participants performed the ipsilateral and contralateral limb coordination tasks at three distinct frequencies: 20, 60, and 100 % of their individually determined CFs (Fig. 1b) for that particular coordination mode. All frequencies were paced by the visual metronome.

To measure the attentional load associated with each coordination pattern, a dual-task paradigm was employed. This involved the concurrent performance of the interlimb coordination task and an auditory probe reaction time task. During dual-task trials, participants were informed that the interlimb coordination task was the primary task and that they were to respond to the randomly presented auditory probe stimuli by saying the word 'tone' as quickly as possible. The probe RT task was also performed as a single task to provide a baseline RT measure. Five auditory stimuli were presented randomly during the 15 s trials with an inter-stimulus interval between 600 and 4,000 ms. For each limb combination (ipsilateral/contralateral), three trials were performed at each frequency under both single-task (coordination task only) and dual-task (coordination task and probe reaction time) conditions, making 36 trials in total. The duration of each trial was 15 s. Similarly for single-task RT trials, mean RT was obtained from three 15 s trials. The order of the conditions was counter balanced across participants. Prior to the experimental session, the motor task was practiced for 5–15 min until participants felt comfortable performing the task.

Data analysis and measures

Attentional load measure

Vocal reaction time to probe stimuli was taken as a measure of attentional load during dual-task performance. Response time was defined as the time interval between the onset of probe stimuli and the onset of vocal response. Response times exceeding the range $M \pm 2SD$ in a condition were discarded to minimize the influence of outliers.

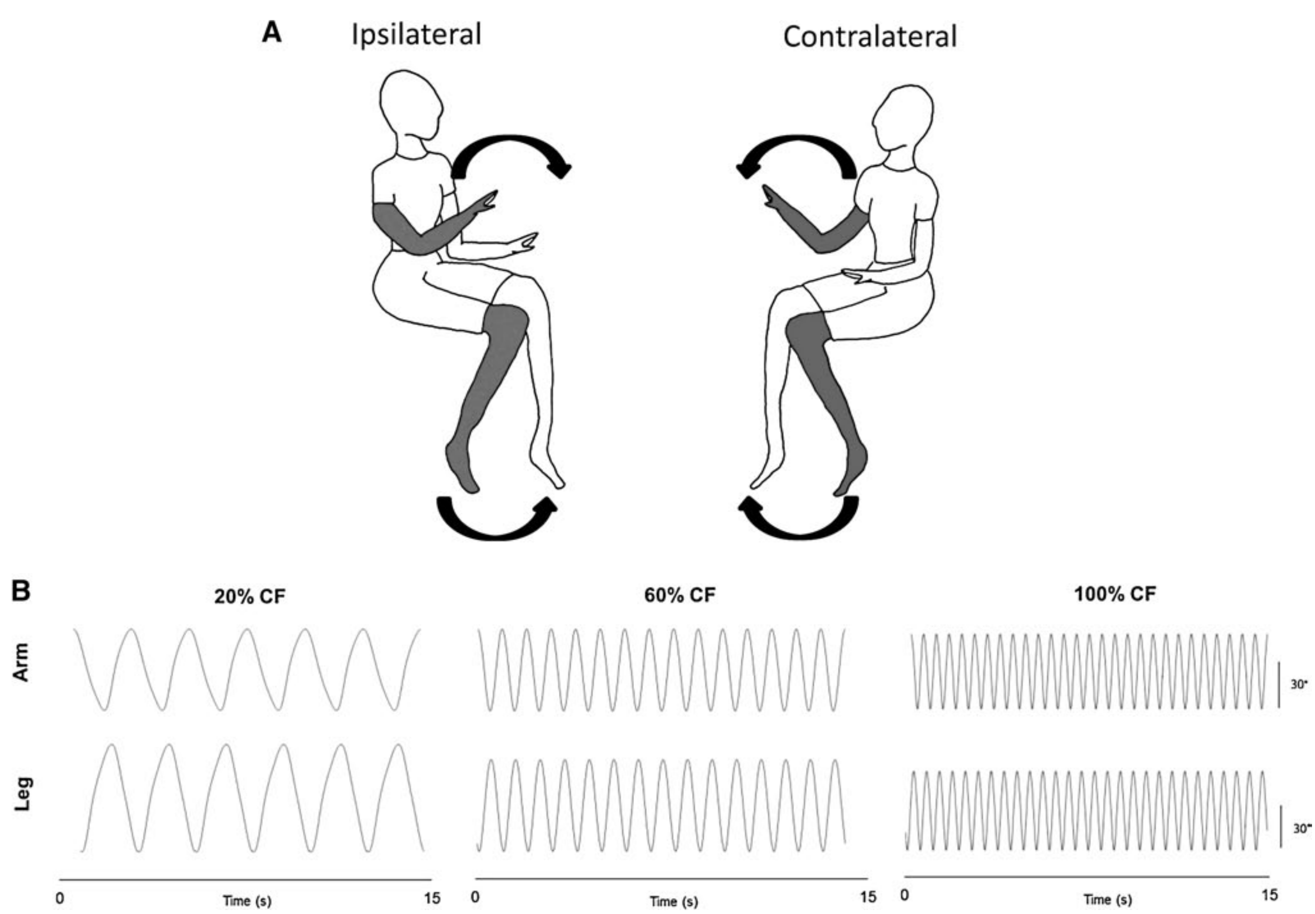


Fig. 1 **a** Cyclical coordination of the arm and leg in the non-isodirectional mode (both segments are moved in opposite directions) with ipsilateral limbs (right arm and right leg) and contralateral limbs (right arm and left leg). *Shaded limbs* represent involved limbs in the coordination pattern. **b** Arm and leg displacements recorded from a single participant during the non-isodirectional coordination mode at 20, 60, and 100 % CF

Spatiotemporal measures

The mean amplitude of limb movements was obtained by averaging the peak-to-peak amplitude of each cycle across the whole trial. Frequency deviation was calculated by subtracting the frequency produced by individual participants from the goal frequency (determined from each participant's critical frequency, CF) for a particular condition, and reflects temporal accuracy. Cycle duration was defined as the time elapsed between two successive peaks in the position-time trace. The variability of the cycle durations within each trial was assessed using the coefficient of variation (CV), defined as the standard deviation of cycle durations within each trial divided by mean cycle duration of that trial. CV therefore reflects temporal stability of the produced movement pattern.

Coordination performance measures (accuracy and variability)

Estimates of relative phase were obtained using the following procedure. The amplitude within each half cycle (peak-to-valley, valley-to-peak) was rescaled to the range [1–1] resulting in a transformed displacement time series approximating a cosine function. Continuous phase angles (degree) for each limb were obtained by taking the arccosine of each point on the scaled time series; continuous relative phase was then the arithmetic difference of the phase angles of the two limbs at each point. Circular statistics (Mardia 1972) were utilized to calculate the mean relative phase and the standard deviation (SD) of relative phase over each cycle of oscillation. Absolute error (AE) of relative phase was obtained as a measure of accuracy by averaging the absolute deviation from mean target relative phase (180°), while the standard deviation (SD) of relative phase was used as a measure of pattern stability. Heuninckx et al. (2004) defined an acceptable deviation from the required non-isodirectional pattern as less than 50° for AE and 30° for SD of relative phase, while Calvin et al. (2004) used the AE range = 180° ± 90° as acceptable performance. Based on these two previously used criteria, the current study only included in data analysis patterns produced with AE and SD of relative phase not exceeding 70° and 50°, respectively.

Statistical analysis

In presenting the results, data are expressed as $M \pm 95$ % confidence intervals. The data were examined using repeated measures ANOVAs applying Huynh–Feldt epsilon corrections when necessary and using Tukey's HSD for post hoc analyses when appropriate. Factors were Group (younger, older), Limb (arm, leg), Limb Combination (ipsilateral, contralateral), Task (single, dual), and Frequency (20, 60, 100 % CF). The level of significance was set at $p < 0.05$. Cohen's d and partial eta squared (η_p^2) values are provided as measures of effect size with cutoffs ≥0.2 small, ≥0.5 medium, ≥0.8 large for Cohen's d and ≥0.01 small, ≥0.06 medium, and ≥0.14 large for η_p^2 (Sink and Stroh 2006).

Results

On the basis of the exclusion criteria for coordination accuracy and stability in older adults, the group means for rejection rate at 100 % CF were 7.5 % (of the trials) in the single-task condition and 12.5 % in the dual-task condition during performance of the ipsilateral limb combination. Rejection rates at 100 % CF for the contralateral limb combination both in single- and dual-task conditions were <7.5 % of the trials in older adults. For younger participants, the number of trials excluded in any condition did not exceed 2.5 %. There were no group differences in arcsine transformed rejection rates (Sheskin 2003) in any of the condition, $ts < 1.59$, $ps > 0.13$, $ds < 0.65$.

An overview of statistical analyses for each dependent variable is presented in Table 1. As age-related changes in interlimb coordination were of primary interest in the present study, only main effects and interactions involving Group as a factor will be described in detail.

Attentional load measure: reaction time

Those trials which were discarded on the basis of RT criteria ($M \pm 2SD$) were too few ($Ms_{young} < 4.2$ %; $Ms_{older} < 3.1$ %, Modes = 0 for all conditions) to analyze and were not included in the analyses of RT.

To examine whether performing two tasks at the same time was particularly difficult for older adults, a 2 × 2 (Group: young, older × Task: single-task, dual-task) ANOVA was conducted. For this particular comparison, we pooled RT from all dual-task coordination modes to compare to RT when the reaction time task was conducted in isolation. We observed significant main effects of Group, $F(1, 22) = 10.72$, $p = 0.003$, $\eta_p^2 = 0.33$, and Task, $F(1, 22) = 71.30$, $p < 0.001$, $\eta_p^2 = 0.76$. Importantly, there was a significant interaction between Group and Task, $F(1, 22) = 4.68$, $p = 0.042$, $\eta_p^2 = 0.18$. Post hoc comparisons indicated that, although both groups showed RT slowing in dual-task conditions (younger, 381 ± 10 ms; older, 448 ± 14 ms) relative to the single task (younger, 323 ± 12 ms; older, 349 ± 8 ms) ($ps < 0.001$), an age difference in RT was only evident under dual-task conditions (single, $p = 0.42$; dual, $p = 0.002$).

Table 1 Summary of main effects and interactions involving Group as a factor for individual ANOVAs on each dependent variable

	df	RT		Amplitude		Amplitude variability		Frequency deviation		Frequency variability		AE of RP		SD of RP	
		F	η_p^2	*F*	η_p^2	*F*	η_p^2	*F*	η_p^2	*F*	η_p^2	*F*	η_p^2	*F*	η_p^2
Main effect															
Group	1,22	**11.84****	0.35	2.99	0.12	1.28	0.06	0.24	0.01	1.63	0.07	**10.91****	0.33	**27.20*****	0.55
Task	1,22	–	–	**11.07****	0.33	3.72	0.14	**13.86****	0.39	0.41	0.02	0.00	0.00	3.24	0.13
Limb	1,22	–	–	0.00	0.00	0.59	0.03	0.00	0.00	0.04	0.00	–	–	–	–
Limb Combination	1,22	**5.55***	0.20	**17.36*****	0.44	1.93	0.08	0.27	0.01	**11.31****	0.34	0.00	0.00	**5.31***	0.19
Frequency	1,22	**38.89*****	0.63	**11.96*****	0.35	**10.20*****	0.32	**43.38*****	0.66	**23.39*****	0.52	**82.72*****	0.79	**45.64*****	0.67
Two-way interaction															
Group × Task	2,44	–	–	0.08	0.00	0.01	0.00	1.74	0.07	0.00	0.00	1.21	0.05	4.37*	0.17
Group × Limb	2,44	–	–	0.01	0.00	1.46	0.06	0.14	0.01	0.33	0.01	–	–	–	–
Group × Limb Combination	2,44	0.27	0.01	0.15	0.01	3.59	0.14	1.70	0.07	2.25	0.09	0.00	0.00	0.20	0.01
Group × Frequency	2,44	**8.51*****	0.04	**6.78****	0.24	0.71	0.03	**5.98****	0.21	**3.97***	0.15	2.56	0.10	0.31	0.01
Three-way interaction															
Group × Task × Limb	2,44	–	–	0.92	0.04	3.00	0.12	0.08	0.00	1.50	0.06	–	–	–	–
Group × Task × Limb Combination	2,44	–	–	0.18	0.01	1.19	0.05	0.12	0.01	2.29	0.09	2.45	0.10	1.33	0.06
Group × Task × Frequency	2,44	–	–	3.61*	0.14	3.18	0.13	1.61	0.07	0.38	0.02	1.08	0.05	**4.21***	0.16
Group × Limb × Limb Combination	2,44	–	–	1.84	0.08	0.53	0.02	0.37	0.02	0.93	0.04	–	–	–	–
Group × Limb × Frequency	2,44	–	–	**13.76*****	0.38	**4.44***	0.17	0.41	0.02	0.01	0.00	–	–	–	–
Group × Limb Combination × Frequency	2,44	1.97	0.04	1.68	0.07	0.69	0.03	1.14	0.05	0.82	0.04	1.23	0.05	1.40	0.06
Four-way interaction															
Group × Task × Limb × Limb Combination	2,44	–	–	2.13	0.10	0.01	0.00	0.24	0.01	3.79	0.15	–	–	–	–
Group × Task × Limb × Frequency	2,44	–	–	0.11	0.00	0.38	0.02	0.62	0.03	0.29	0.01	–	–	–	–
Group × Task × Limb Combination × Frequency	2,44	–	–	1.05	0.05	0.19	0.01	0.03	0.00	0.18	0.01	1.16	0.05	1.10	0.05
Group × Limb × Limb Combination × Frequency	2,44	–	–	1.12	0.05	0.39	0.02	0.57	0.03	0.80	0.04	–	–	–	–
Five-way interaction															
Group × Task × Limb × Limb Combination × Frequency	2,44	–	–	0.12	0.01	1.88	0.08	0.33	0.01	2.37	0.10	–	–	–	–

Bold values indicate statistically significant results

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

Vocal probe reaction time during dual-task conditions was examined as a measure of attentional cost using a 2 × 2 × 3 (Group × Limb Combination × Frequency) ANOVA with longer RT indicating greater attentional load associated with performance of the primary (coordination) task. A significant main effect of Limb Combination, $F(1, 22) = 5.55$, $p = 0.027$, $\eta_p^2 = 0.20$, indicated that the ipsilateral limb combination (401 ± 15 ms) required more attention than the contralateral limb combination (386 ± 12 ms). There was a significant main effect of Group, $F(1, 22) = 11.84$, $p = 0.002$, $\eta_p^2 = 0.35$, with the older group exhibiting longer reaction time (422 ± 15 ms) than younger adults (364 ± 10 ms). A significant main effect of Frequency, $F(1.77, 38.85) = 38.89$, $p < 0.001$, $\eta_p^2 = 0.63$, indicated that moving the limbs at 20 % CF (459 ± 14 ms) resulted in significantly longer reaction times than 60 % CF and 100 % CF conditions (ps < 0.001, 60 % CF 387 ± 8 ms; 100 % CF 398 ± 8 ms). Importantly, there was a significant interaction of Group × Frequency, $F(1.77, 38.85) = 8.51$, $p = 0.001$, $\eta_p^2 = 0.28$. Post hoc analyses revealed that in older adults, moving the limbs at 20 % CF resulted in significantly slower reaction times compared to 60 % CF and 100 % CF (ps < 0.001) (Fig. 2). For younger adults, RT was significantly longer at 20 % CF than 60 % CF ($p = 0.036$), but no significant difference was observed between RT at 20 % CF and 100 % CF ($p = 0.128$). Furthermore, at 20 % CF, older adults showed significantly slower RT than younger adults ($p < 0.001$), but not at 60 % CF or 100 % CF (ps > 0.23) (see Fig. 2).

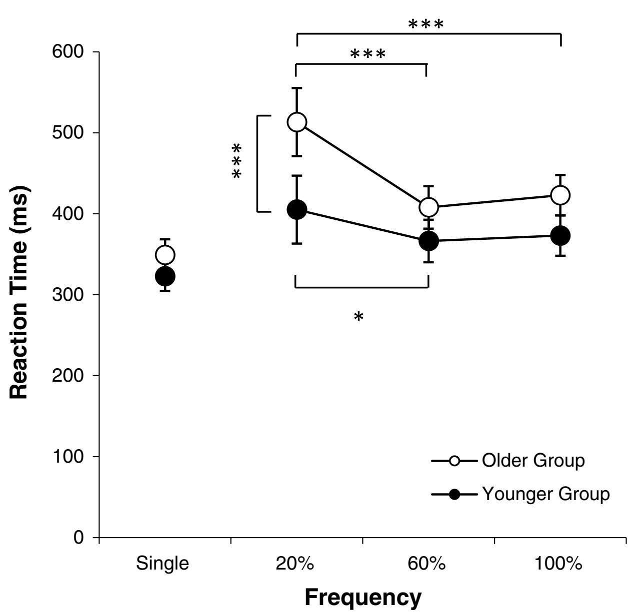


Fig. 2 Mean reaction time (ms) for younger and older adults in single- and dual-task condition across frequency. *Error bars* indicated 95 % CI. *Asterisks* indicate a significant difference (*$p < 0.05$, ***$p < 0.001$)

The Group × Limb Combination × Frequency interaction was not significant ($p = 0.388$, $\eta_p^2 = 0.04$), indicating that both the younger and older groups exhibited increased attentional load for the ipsilateral compared to contralateral limb combination across all movement frequencies.

Spatiotemporal measures

Movement amplitude

There was a significant interaction of Group × Limb × Frequency, $F\ (1.78, 39.24) = 13.76$, $p < 0.001$, $\eta_p^2 = 0.38$. As shown in Fig. 3, in the younger group, the amplitude of both arm and leg movements decreased as frequency increased. In contrast, while older adults showed a similar pattern to their younger counterparts for arm movements, the amplitude of leg movements did not change significantly as a function of frequency. Thus, younger adults accommodated increases in required frequency by reducing the amplitude of both upper- and lower-limb movements, whereas older adults showed only a modulation of upper-limb movement amplitudes.

Movement amplitude variability

There was a significant main effect of Frequency, $F(1.93, 42.53) = 10.20$, $p < 0.001$, $\eta_p^2 = 0.28$, and a significant three-way interaction of Group × Limb × Frequency $F(2,44) = 4.44$, $p = 0.018$, $\eta_p^2 = 0.17$. For arm movements, post hoc comparisons showed no differences in amplitude variability between frequency levels for both younger and older adults. With respect to leg movements, group differences were not significant in any of the conditions (ps > 0.992). However, in older adults, the amplitude variability of leg movements significantly increased as frequency increased ($p < 0.01$), whereas no differences in amplitude variability were observed in the upper-limb movements (ps > 0.99). In contrast, for younger adults, increases in required movement frequency did not result in increases in amplitude variability in either upper or lower limbs (ps > 0.22).

Movement frequency

Critical movement frequency (CF)

While the observed CFs for older adults were slightly lower for both the ipsilateral (1.68 ± 0.20 Hz) and contralateral (1.72 ± 0.22 Hz) limb combinations than for younger adults (1.83 ± 0.12 and 1.88 ± 0.12 Hz, respectively), a 2 (Group) × 2 (Limb Combination) ANOVA revealed that the Group main effect was not significant, $F(1, 22) = 1.98$, $p = 0.170$, $\eta_p^2 = 0.08$. However, the ipsilateral limb

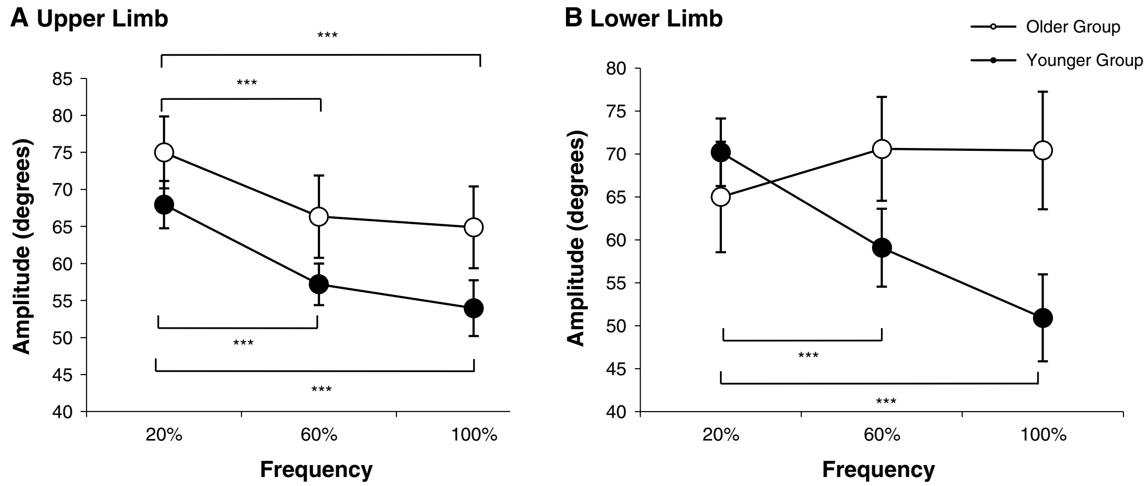


Fig. 3 Mean amplitude of each limb for younger and older adults across frequency. *Error bars* indicated 95 % CI. *Asterisks* indicate a significant difference (*** $p<0.001$)

combination exhibited a significantly lower CF than the contralateral limb combination (Limb Combination main effect, $F(1, 22) = 4.41$, $p = 0.047$, $\eta_p^2 = 0.17$).

Frequency deviation

The only significant effect including Group as a factor was the Group × Frequency interaction, $F(1.24, 27.27) = 5.98$, $p = 0.005$, $\eta_p^2 = 0.21$. Post hoc analyses indicated that although participants in both groups tended to move faster at 20 % CF (younger, 0.02 ± 0.02 Hz; older, 0.11 ± 0.06 Hz) and slower at 100 % CF (younger, −0.18 ± 0.11 Hz; older, −0.35 ± 0.09 Hz) than the target frequencies, these deviations were more pronounced in the older group. A main effect of Task, $F(2, 44) = 13.86$, $p = 0.001$, $\eta_p^2 = 0.39$ (Table 1), indicated that overall participants slowed down to a greater extent during the single-task (−0.08 ± 0.04 Hz) condition than during dual-task condition (−0.04 ± 0.05 Hz).

Frequency variability (CV)

The main effect of Group was not significant, $F(1, 22) = 1.63$, $p = 0.214$, $\eta_p^2 = 0.07$, but there was a significant Group × Frequency interaction, $F(2, 44) = 3.97$, $p = 0.026$, $\eta_p^2 = 0.15$. As illustrated in Fig. 4, older participants exhibited significantly higher CV in the 20 % CF condition (11.69 ± 1.24 %) compared to the other frequencies (60 % CF 6.27 ± 2.05 %; 100 % CF 5.88 ± 0.51 %; *ps* < 0.001). Furthermore, CV at 20 % CF was also significantly higher for older compared to CV at 20 % CF for younger adults (8.30 ± 0.78 %; $p = 0.006$). In contrast, for the younger group, CV did not vary reliably across the different frequencies (60 % CF 6.24 ± 1.79 %; 100 % CF 6.04 ± 0.96 %).

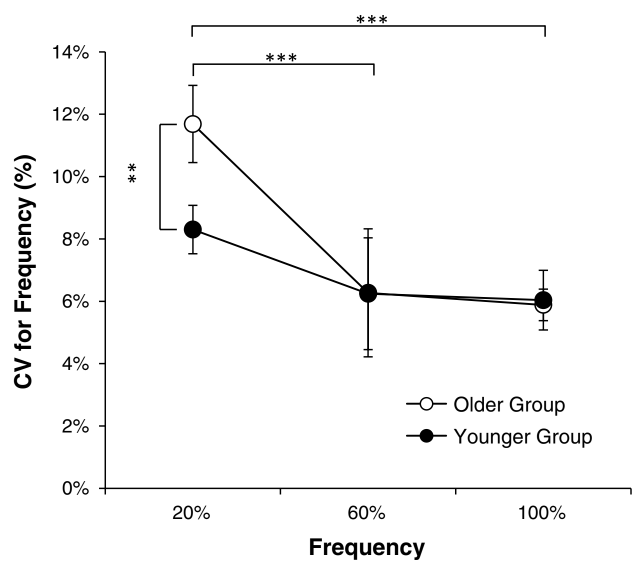


Fig. 4 Mean coefficient of variation (CV) for movement frequency in younger and older adults across frequency. *Error bars* indicated 95 % CI. *Asterisks* indicate a significant difference (*$p < 0.01$, ***$p < 0.001$)

Coordination performance measures

Accuracy of coordination (AE of relative phase)

There was a significant main effect of Group, $F(1, 22) = 10.91$, $p = 0.003$, $\eta_p^2 = 0.33$, with older adults showing greater deviation (22.05 ± 2.98°) from the target relative phase than younger participants (13.87 ± 2.35°). There was also a significant main effect of Frequency, $F(1.87, 41.10) = 82.72$, $p = 0.001$, $\eta_p^2 = 0.79$. Coordination performance was significantly less accurate at 100 % CF (31.00 ± 3.99°) than at the other movement frequencies (20 %, 7.67 ± 1.23°; 60 %, 15.22 ± 2.40°) (*ps* < 0.001). Furthermore, performance at 20 % was significantly more accurate than at 60 % ($p = 0.001$). No other significant main effects or interactions were evident.

Stability of coordination (SD of relative phase)

There was a significant main effect of Limb Combination, $F(1, 22) = 5.31$, $p = 0.031$, $\eta_p^2 = 0.19$, indicating that performance of the ipsilateral limb combination was less stable (19.57 ± 4.69°) than the contralateral limb combination (17.21 ± 2.79°). Of particular interest, however, was the significant three-way interaction of Group × Task × Frequency, $F(1.60, 35.22) = 4.21$, $p = 0.021$, $\eta_p^2 = 0.16$. As shown in Fig. 5, performance was significantly less stable at 100 % CF than at other frequencies for both single-task and dual-task conditions (all *ps* < 0.024). Older adults exhibited a significant reduction in stability at 100 % CF when performing the coordination task under dual-task conditions than as a single task ($p = 0.015$), whereas for younger adults, stability in single- and dual-task trials did not differ significantly ($p = 0.206$). Importantly, an age difference in stability was evident at 100 % CF in the dual-task conditions with older adults exhibiting a lower stability relative to younger adults ($p < 0.001$). The four-way interaction between Group, Task, Limb Combination, and Frequency was not significant, $F(1.32, 29.06) = 1.10$, $p = 0.32$, $\eta_p^2 = 0.05$ (Table 1). In summary, while both groups exhibited the expected reduction in stability when performing at 100 % CF compared to the other tested frequencies, for older adults concurrently performing a probe RT task resulted in a *further* loss of stability, but only at the highest frequency.

Discussion

The present study examined age-related changes in the attentional cost associated with the production of non-isodirectional arm and leg movements performed at different movement frequencies. Of particular interest was the level of attentional cost required when interlimb coordination was performed at a slow movement frequency. While performance at 20 % CF and 60 % CF was not significantly different in terms of coordination measures (accuracy and stability), moving at the slower frequency incurred greater attentional cost, particularly for the older adults.

In line with previous studies (Greene and Williams 1996; Heuninckx et al. 2004; Lee et al. 2002), age-related decline in interlimb coordination (as indicated by greater relative phase variability) was observed at a movement frequency close to individual's predetermined maximal movement frequency when the coordination task was performed concurrently with the attention task. Furthermore, non-isodirectional patterns involving coordination of ipsilateral limbs exhibited higher variability in relative phase ore and were more attentionally demanding than patterns involving coordination of contralateral limbs (Hiraga et al.

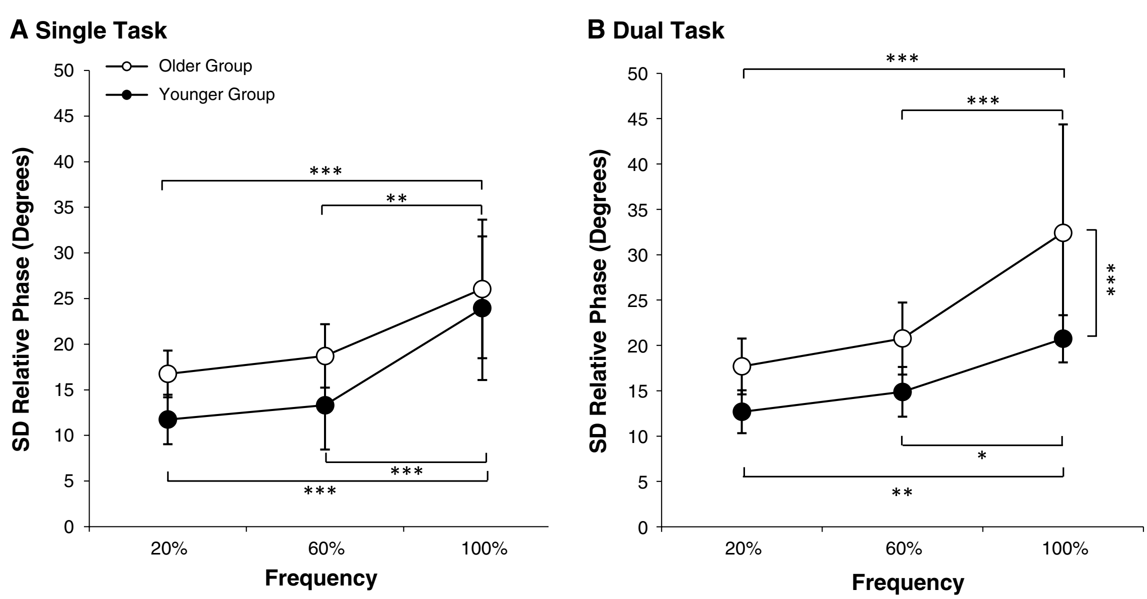


Fig. 5 Standard deviation of relative phase for younger and older adults in **a** single- and **b** dual-task condition across frequency. *Error bars* indicated 95 % CI. *Asterisks* indicate a significant difference (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$)

2004, 2005; Meesen et al. 2006). Somewhat unexpectedly, for both age groups, attentional load required to perform the coordination task at a very fast speed (100 % CF) was not different to the attentional load required at a moderate speed (60 % CF) which has been shown to be less attentionally demanding (Monno et al. 2000). This observation is likely related to the fact that both young and older groups adopted a movement frequency lower than their predetermined CF in the 100 % CF condition. In line with other studies of aging effects on interlimb coordination (Serrien et al. 2000; Wishart et al. 2000), the tendency to sacrifice speed for accuracy was more evident in older than younger adults and may result from the lack of modulation of movement amplitude across movement frequencies by older adults.

Of particular interest in the current study, however, was the ability to perform interlimb coordination at a particularly slow movement frequency, and the associated attentional cost. While performance at 20 % CF was significantly more accurate, as judged by lower relative phase error, than at 60 % CF, the attentional load associated with producing the desired movement pattern was also significantly higher at the slower rate. This was particularly the case for older adults as an age difference in attentional cost was observed only at the slowest frequency (Fig. 2). We note that at these lower frequencies, both age groups exhibited similar movement amplitudes. As such, group differences in amplitude modulation (as observed at 100 % CF) cannot explain the group differences in attentional cost. These findings are consistent with the idea that very slow movements involve higher-level timing mechanisms, which are less automated than the more intrinsic low-level timing mechanisms that mediate faster movements. Krampe et al. (2010) recently proposed a two level timing system after observing that slow unimanual tapping was associated with higher attention requirements than fast unimanual tapping. The current study is the first to indicate that very slow interlimb coordination may also be very attentionally demanding. Consistent with the notion of reduced automaticity, although older adults performed the slowest interlimb coordination pattern with high accuracy and stability (with respect to the desired relative phase), they exhibited significantly increased cycle duration variability relative to the other frequencies (Fig. 4). This finding suggests that for older adults, the movements at the slowest movement frequency may have become more discontinuous. Indeed, there is some kinematic evidence from previous studies to suggest that when continuous cyclic arm movements are performed at a sufficiently slow rate, they appear to be produced as a series of discrete movements (Nagasaki 1991; van der Wel et al. 2010). The control of discontinuous movements is likely to require a higher level of processing relative to continuous, rhythmic movements. Indeed, using a dual-task paradigm Summers et al. (2008) showed that bimanual discontinuous circle drawing movements required greater attentional resources to execute than continuous cyclical movements. Furthermore, a recent imaging study reported that a greater volume of motor cortex was activated, and a higher blood-oxygen-level–dependent (BOLD) signal was measured in a movement tracking task undertaken at a slow movement frequency (0.4 Hz) compared to a non-tracking simple movement task performed at comfortable speed (Carey et al. 2006). The observed increase in attentional cost at 20 % CF in the present study is therefore consistent with the view that increased 'discreteness' of movement requires an increased degree of cognitive involvement in timing control (Lewis and Miall 2003; Schaal et al. 2004).

Research examining timing mechanisms underlying repetitive movements have suggested that an *event timing* function controls discrete movements, characterized by distinct pauses within each movement cycle. This control is believed to be mediated within the cerebellum (Spencer et al. 2003). In discrete movement tasks, explicit representation of an individual temporal goal is required for successive discrete events to initiate each movement cycle (Zelaznik et al. 2002). In contrast, continuous movements such as circle drawing are controlled by an *emergent timing* system. This system is more automatic than event timing, where temporal consistency is seen as an emergent property of trajectory formation and control processes (Summers et al. 2010). Automatic timing primarily recruits circuits within the motor system that can track time without modulation by attentional processes (Lewis and Miall 2003; Schaal et al. 2004) since these tasks do not rely on explicit temporal control once initiated (Zelaznik et al. 2002). With respect to the effect of aging on timing mechanisms involved in a motor task, a recent study from our group (Summers et al. 2010) revealed that older adults can match the performance of younger adults when the task required automatic (emergent) timing mechanisms (continuous bimanual circling task), whereas the temporal consistency of an intermittent circling task, requiring higher-level timing processes (event timing), was significantly more variable in older than younger adults. Our current findings in which older adults showed similar temporal consistency with younger adults at 60 and 100 % CF, but not at 20 % CF, are consistent with this previous finding. It appears, therefore, that coordination performance at 20 % CF, which exhibited the characteristics of a set of discrete movements with large temporal variability, was controlled by cognitively demanding higher-level timing mechanisms, particularly in older adults.

There is some evidence that the ability to perform slower discrete movements, which rely on event timing, declines in older adults. For example, using a bimanual tapping task in which both hands were required to tap at the same time, Bangert et al. (2010) demonstrated a decline in event timing processes with advancing age, particularly at longer tapping intervals. In their study, age differences in the temporal asynchrony between hands increased as inter-tap interval (ITI) increased, suggesting reduced sensitivity of event timing processes. Furthermore, McAuley et al. (2006) found that older adults experienced the greatest difficulty synchronizing unilateral finger taps with auditory pacing stimuli at slower rates. The authors explained the observed outcomes with an entrainment region hypothesis. The hypothesis predicts that the range (region) of frequency in which an individual can accurately track events in the environment increases through adolescence and then narrows down later in life. The current data are consistent with this idea (i.e., the greatest temporal variability and attentional cost at the slowest movement frequency in older adults can be seen as a manifestation of decreased entrainment region with aging). The study by McAuley et al. (2006) also suggests that older adults may have greater difficulty in producing slower movements regardless of whether they require complex coordination of two limbs in time with a auditory metronome (i.e., as required in the current study and Bangert et al. 2010) or only involve a single effector. That is, in addition to the increased difficulty at 20 % CF in the current study due to the discreteness of the movement, it may also be the case that the control of slow movements per se (<1 Hz) requires higher attentional cost than faster movements (see Lewis and Miall 2003 for further discussion regarding control of dual dimensions in coordinated movement control, that is, 'discreteness of movement' and 'movement timing').

In summary, non-isodirectional coordination of upper and lower limbs at a particularly slow rate increased the discreteness of movements (measured by frequency variability), which required greater attentional cost involving higher-level timing processes (event timing) to synchronize movements with the visual metronome. In contrast, in line with previous studies (Baldissera et al. 1982, 1991; Carson et al. 1995), there was a loss of stability when the non-isodirectional interlimb coordination was performed at the fastest rate (100 % CF). In summary, older adults exhibited less stable performance than younger adults at the fastest movement frequency, particularly when the probe RT task was performed concurrently. Thus, the effects of aging on overt measures of interlimb coordination performance are most apparent in tasks where the motor system is challenged, and when those tasks carry significant attentional weight (i.e., dual-task situations). However, the attentional demand associated with the coordination task was greatest at the slowest cycling frequency due to the shift of movement trajectory control from smooth and rhythmic to being more discrete in nature with the resultant increased involvement of higher-level timing mechanisms. Overall, the results of this study demonstrate that moving 'slow and steady' comes with the cost of increased attentional demands, particularly in older adults. This finding has clear theoretical implications in terms of our understanding of motor control across the life span. Moreover, the findings have practical relevance, insofar as how best to implement motor learning (e.g., with respect to sport and musical training) and rehabilitation (e.g., recovery of motor function post-stroke).

Acknowledgments This research was supported under Australian Research Council's *Discovery Projects* funding scheme (Project Number DP0770568).

References

Baldissera F, Cavallari P, Civaschi P (1982) Preferential coupling between voluntary movements of ipsilateral limbs. Neurosci Lett 34:95–100. doi:10.1016/0304-3940(82)90098-2

Baldissera F, Cavallari P, Marini G, Tassone G (1991) Differential control of in-phase and anti-phase coupling of rhythmic movements of ipsilateral hand and foot. Exp Brain Res 83:375–380. doi:10.1007/BF00231161

Bangert AS, Reuter-Lorenz PA, Walsh CM, Schachter AB, Seidler RD (2010) Bimanual coordination and aging: neurobehavioral implications. Neuropsychologia 48:1165–1170

Calvin S, Milliex L, Coyle T, Temprado JJ (2004) Stabilization and destabilization of perception-action patterns influence the self-organized recruitment of degrees of freedom. J Exp Psychol Hum Percept Perform 30:1032–1042. doi:10.1037/0096-1523.30.6.1032

Carey JR, Greer KR, Grunewald TK, Steele JL, Wiemiller JW, Bhatt E, Nagpal A, Lungu O, Auerbach EJ (2006) Primary motor area activation during precision-demanding versus simple finger movement. Neurorehabil Neural Repair 20:361–370. doi:10.1177/1545968306289289

Carson RG, Goodman D, Kelso JAS, Elliott D (1995) Phase-transitions and critical fluctuations in rhythmic coordination of ipsilateral hand and foot. J Mot Behav 27:211–224. doi:10.1080/00222895.1995.9941711

Commodari E, Guarnera M (2008) Attention and aging. Aging Clin Exp Res 20:578–584. doi:10.1111/j.1600-0447.1993.tb03355.x

de Rekeneire N, Visser M, Peila R, Nevitt MC, Cauley JA, Tylavsky FA, Simonsick EM, Harris TB (2003) Is a fall just a fall: correlates of falling in healthy older persons. The health, aging and body composition study. J Am Geriatr Soc 51:841–846. doi:10.1046/j.1365-2389.2003.51267.x

Dick JPR, Guiloff RJ, Stewart A, Blackstock J, Bielawska C, Paul EA, Marsden CD (1984) Mini-mental state examination in neurological patients. J Neurol Neurosurg Psychiatry 47:496–499. doi:10.1136/jnnp.47.5.496

Fujiyama H, Garry MI, Levin O, Swinnen SP, Summers JJ (2009) Age-related differences in inhibitory processes during interlimb coordination. Brain Res 1262:38–47. doi:10.1016/j.brainres.2009.01.023

Fujiyama H, Garry MI, Martin FH, Summers JJ (2010) An ERP study of age-related differences in the central cost of interlimb coordination. Psychophysiology 47:501–511. doi:10.1111/j.1469-8986.2009.00954.x

Goldberger AL, Amaral LAN, Hausdorff JM, Ivanov PC, Peng CK, Stanley HE (2002) Fractal dynamics in physiology:

alterations with disease and aging. p 2466–2472. doi:10.1073/pnas.012579499
Greene LS, Williams HG (1996) Aging and coordination from the dynamic pattern perspective. In: Ferrandez AM, Teasdale N (eds) Change in sensory motor behavior in aging. Elsevier Science B.V., Holland, pp 89–131. doi:10.1036/0070244286
Heuninckx S, Debaere F, Wenderoth N, Verschueren S, Swinnen SP (2004) Ipsilateral coordination deficits and central processing requirements associated with coordination as a function of aging. J Gerontol B Psychol Sci Soc Sci 59:225–232. doi:10.1093/geronb/59.5.P225
Hiraga CY, Summers JJ, Temprado JJ (2004) Attentional costs of coordinating homologous and non-homologous limbs. Hum Mov Sci 23:415–430. doi:10.1016/j.humov.2004.08.015
Hiraga CY, Summers JJ, Temprado JJ (2005) Effects of attentional prioritisation on the temporal and spatial components of an interlimb circle-drawing task. Hum Mov Sci 24:815–832. doi:10.1016/j.humov.2005.10.010
Hunter SK, Thompson MW, Adams RD (2001) Reaction time, strength, and physical activity in women aged 20–89 years. J Aging Phys Act 9:32–42
Kelso JAS, Jeka JJ (1992) Symmetry breaking dynamics of human multilimb coordination. J Exp Psychol Hum Percept Perform 18:645–668. doi:10.1037/0096-1523.18.3.645
Krampe RT, Doumas M, Lavrysen A, Rapp M (2010) The costs of taking it slowly fast and slow movement timing in older age. Psychol Aging 25:980–990. doi:10.1037/a0020090
Lee TD, Wishart LR, Murdoch JE (2002) Aging, attention, and bimanual coordination. Can J Aging 21:549–557. doi:10.1017/S0714980800002087
Lewis PA, Miall RC (2003) Distinct systems for automatic and cognitively controlled time measurement: evidence from neuroimaging. Curr Opin Neurobiol 13:250–255. doi:10.1016/S0959-4388(03)00036-9
Li SC, Sikstrom S (2002) Integrative neurocomputational perspectives on cognitive aging, neuromodulation, and representation. Neurosci Biobehav Rev 26:795–808. doi:10.1016/S0149-7634(02)00066-0
Lipsitz LA (2004) Physiological complexity, aging, and the path to frailty. Science of aging knowledge environment: SAGE KE 2004: pe16. doi:10.1126/sageke.2004.16.pe16
Mardia KV (1972) Statistics of directional data. Academic Press, London
McAuley JD, Jones MR, Holub S, Johnston HM, Miller NS (2006) The time of our lives: life span development of timing and event tracking. J Exp Psychol Gen 135:348–367. doi:10.1037/0096-3445.135.3.348
Meesen RLJ, Wenderoth N, Temprado JJ, Summers JJ, Swinnen SP (2006) The coalition of constraints during coordination of the ipsilateral and heterolateral limbs. Exp Brain Res 174:367–375. doi:10.1007/s00221-006-0471-1
Monno A, Chardenon A, Temprado JJ, Zanone PG, Laurent M (2000) Effects of attention on phase transitions between bimanual coordination patterns: a behavioral and cost analysis in humans. Neurosci Lett 283:93–96
Morgan M, Phillips JG, Bradshaw JL, Mattingley JB, Iansek R, Bradshaw JA (1994) Age-related motor slowness: simply strategic. J Gerontol 49:M133–M139. doi:10.1093/geronj/49.3.M133
Nagasaki H (1991) Asymmetrical trajectory formation in cyclic forearm movements in man. Exp Brain Res 87:653–661. doi:10.1007/BF00227091
Newell KM, Vaillancourt DE, Sosnoff JJ (2006) Aging, complexity and motor performance: healthy and disease states. In: Birren JE, Schaie KW (eds) Handbook of the psychology of aging, 6th edn. Elsevier, Amsterdam, pp 163–182
Salthouse TA (1991) Theoretical perspective on cognitive aging. Lawrence Erlbaum Associates, Hillsdale
Salthouse TA (1996) The processing-speed theory of adult age differences in cognition. Psychol Rev 103:403–428. doi:10.1037/0033-295X.103.3.403
Schaal S, Sternad D, Osu R, Kawato M (2004) Rhythmic arm movement is not discrete. Nat Neurosci 7:1136–1143. doi:10.1038/nn1322
Serrien DJ, Swinnen SP (1997) Coordination constraints induced by effector combination under isofrequency and multifrequency conditions. J Exp Psychol Hum Percept Perform 23:1493–1510. doi:10.1037/0096-1523.23.5.1493
Serrien DJ, Swinnen SP, Stelmach GE (2000) Age-related deterioration of coordinated interlimb behavior. J Gerontol Psychol Sci 55B:295–303
Sheskin DJ (2003) Handbook of parametric and nonparametric statistical procedures, 3rd edn. CRC Press, Boca Raton
Sink CA, Stroh HR (2006) Practical significance: the use of effect sizes in school counseling research. Prof Sch Couns 9:401–411
Spencer RMC, Zelaznik HN, Diedrichsen J, Ivry RB (2003) Disrupted timing of discontinuous but not continuous movements by cerebellar lesions. Science 300:1437–1439. doi:10.1126/science.1083661
Spirduso WW (1995) Physical dimensions of aging. Champaign. Human Kinetics, Champaign
Summers JJ, Maeder S, Hiraga CY, Alexander JRM (2008) Coordination dynamics and attentional costs of continuous and discontinuous bimanual circle drawing movements. Hum Mov Sci 27: 823–837. doi:10.1016/j.humov.2007.11.003
Summers JJ, Lewis J, Fujiyama H (2010) Aging effects on event and emergent timing in bimanual coordination. Hum Mov Sci 29:820–830. doi:10.1016/j.humov.2009.10.003
Swinnen SP (2002) Intermanual coordination: from behavioural principles to neural-network interactions. Nat Rev Neurosci 3:350–361. doi:10.1038/nrn807
Temprado JJ, Zanone PG, Monno A, Laurent M (2001) A dynamical framework to understand performance trade-offs and interference in dual tasks. J Exp Psychol Hum Percept Perform 27:1303–1313. doi:10.1037/0096-1523.27.6.1303
Vaillancourt DE, Newell KM (2002) Changing complexity in human behavior and physiology through aging and disease. Neurobiol Aging 23:1–11
van der Wel R, Sternad D, Rosenbaum DA (2010) Moving the arm at different rates: slow movements are avoided. J Mot Behav 42:29–36. doi:10.1080/00222890903267116
Walker N, Philbin DA, Spruell C (1996) The use of signal detection theory in research on age-related differences in movement control. In: Rogers WA, Fisk AD, Walker N (eds) Aging and skilled performance. Lawrence Erlbaum Associates, Mahwah
Welford AT (1988) Reaction time, speed of performance, and age. In: Joseph JA (ed) Central determination of age-related declines in motor function, vol 515. Annals of the New York Academy of Sciences, NY, pp 1–17
Wishart LR, Lee TD, Murdoch JE, Hodges NJ (2000) Effects of aging on automatic and effortful processes in bimanual coordination. J Gerontol Psychol Sci 55B:85–94
Zacks RT, Hasher L, Li KZH (2000) Human memory. In: Craik FIM, Salthouse TA (eds) The handbook of aging and cognition. Lawrence Erlbaum Associates, Inc., Mahwah, pp 293–357
Zelaznik HN, Spencer RMC, Ivry RB (2002) Dissociation of explicit and implicit timing in repetitive tapping and drawing movements. J Exp Psychol Hum Percept Perform 28:575–588. doi:10.1037//0096-1523.28.3.575