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RESEARCH ARTICLE

Perceptuo-motor learning rate declines by half from 20s to 70/80s

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Abstract This study examined perception–action learning in younger adults in their 20s compared to older adults in their 70s and 80s. The goal was to provide, for the first time, quantitative estimates of perceptuo-motor learning rates for each age group and to reveal how these learning rates change between these age groups. We used a visual coordination task in which participants are asked to learn to produce a novel-coordinated rhythmic movement. The task has been studied extensively in young adults, and the characteristics of the task are well understood. All groups showed improvement, although learning rates for those in their 70s and 80s were half the rate for those in their 20s. We consider the potential causes of these differences in learning rates by examining performance across the different coordination patterns examined as well as recent results that reveal age-related deficits in motion perception.

Keywords Rhythmic coordination · Older adults · Aging · Learning · Perception

Introduction

Many daily activities like cooking, eating, getting dressed, or locomotion (by foot or by automobile) entail the coordination of perception and action. Older adults are often required to re-learn such coordination skills following injury or stroke, or alternatively to learn new forms of coordination (e.g., one-handed/multi-finger dressing, walking with aids). Whether and how the ability to learn such skills changes with age is therefore of great interest: impairments in learning could cause older adults to become increasingly dependent on others for care. This would negatively affect not only their health and recovery from injury (especially if care is not available) but also society in general due to potential institutionalization and increases in caregiver burden.

There have, however, been surprisingly few investigations of changes in perceptuo-motor learning that occur with advanced aging, even though the ability to learn new patterns of coordination underpins rehabilitation practice. The most recent systematic review found a mere 25 scientific articles up to 2007 (Voelcker-Rehage 2008), More recent articles focusing on percepto-motor learning have been published (e.g., Ghisletta et al. 2010; Panzer et al. 2011), but importantly, both prior to and since this review, none have attempted to evaluate changes in perceptuo-motor by quantifying learning *rates*.

A useful and established way of assessing perceptuo-motor learning is through studies of *coordinated rhythmic movement* (first described by Kelso 1981). Initially, rhythmic movement coordination was studied in young adults using the now classic finger extension-flexion paradigm (Kelso 1984). This coordination has been modeled as a pair of coupled oscillators that exhibit coordination as an emergent pattern of behavior (Bingham 2004a, b; Haken

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et al. 1985; Kay et al. 1987; Snapp-Childs et al. 2011; Yamanishi et al. 1980). The coordination is represented as a phase relation—when the fingers move upward and downward at the same time they are moving in-phase (0° relative phase); when the fingers move in opposition, one moving upward when the other is moving downward, they are moving in anti-phase (180°). Many studies have shown that the most stable form of coordination is 0°. 180° relative phase can also be produced readily, but it is less stable than 0°. Both patterns are said to reflect the intrinsic dynamics of the system as they do not require learning (Swinnen et al. 1998) and can be produced without much intent or conscious effort (Zanone and Kelso 1992). Other coordination patterns such as 90° are difficult, if not impossible, to produce without special training or special circumstances (e.g., following a couple of metronomes; Serrien et al. 2000; Swinnen et al. 1998; Yamanishi et al. 1980; Zanone and Kelso 1992).

Coordinated rhythmic movement and perceptuo-motor learning

Zanone and Kelso (1992) argued that 90° is hard to produce due to a need to overcome the strong tendency to perform one of the intrinsic patterns (0° or 180°). They suggested that the two relative phase patterns act as “attractors” to which people are drawn while trying to produce other relative phase patterns. The problem with this account was that there is no explanation for the origin of the attractors; why are they at 0° and 180° and not elsewhere? The hypothesis now is that these attractors are where they are because of the nature of the perceptual coupling between the limbs. Strong evidence that coordination is mediated by perception was first provided by *visual coordination* studies where the participant oscillates one limb to coordinate with oscillatory movement of another person or in a display controlled by a computer. Schmidt et al. (1990) and Temprado et al. (2003) showed that all the coordination dynamics are exhibited when two different people coordinate their respective limb movements. In this case, only vision is available and used to couple the two limb movements. The coordination patterns also arise in coordination between a participant and a display (e.g., Wimmers et al. 1992; Wilson et al. 2005a), where participants move one limb (or oscillator) to coordinate with a second computer-controlled oscillator at a particular phase relation. This unimanual coordination differs from bimanual coordination, where the participant must produce both movements in a coordinated fashion so as to generate the desired phase relation. By hypothesis, the coupling is still perceptual in this case as well. More research confirmed that coordination is perceptually mediated (Bingham et al. 1999; Mechsner et al. 2001; Wimmers et al. 1992; Zaal et al. 2000; Bingham 2001), and this led to a *perception–action* perspective on coordination where the perceptual information is considered a crucial element (Bingham 2004a, b). Subsequently, additional studies demonstrated that the detection and use of visual information (e.g., Wilson et al. 2005a, b, 2010a) and/or kinesthetic information (Wilson et al. 2003) about relative phase yields the characteristic dynamic patterns in movement. In the context of this perception–action understanding of coordination, the inability to produce rhythmic coordination at 90° is hypothesized to result from an inability to identify the 90° phase relation, that is, to perceive and recognize it. If an actor cannot identify 90° and distinguish it from other phase relations, then he or she cannot recognize the failure to produce 90°, and therefore, corrections to the movement cannot be made to maintain a 90° coordination. However, with training, observers can learn to perceive new information that enables them to clearly perceive 90° (Wilson and Bingham 2008), and this then enables stable movement at 90° (Wilson et al. 2010a). People require stable access to perceptual information in order to produce stable action.

Evidence for this perception–action hypothesis about movement stability and learning has been provided by two types of studies. The first type of study shows that movements at 90° can be stabilized if the feedback display is transformed to be more easily perceived and used by the actor. Wilson et al. (2005a, b) showed that participants were well able to move their limb at 90° relative to the movement controlled by the computer if the phase relation that they were visually perceiving and controlling was transformed to show 0°, whereas if they simply attempted to generate the 90° coordination without this information, they could not. This demonstrated that if the result of the movement is easily perceived, the movement can be easily maintained. A number of recent studies have shown that participants are able to quickly and reliably produce stable 90° coordination when the visual information used to control and generate the movements was transformed to a Lissajous display, that is, a position–position plot (Kovacs et al. 2009a, b). In this case, a 90° movement yields a circle in the display, and the task is simply to move so as to keep a single cursor on the circle. This makes it easy to detect when you are moving at 90° and when you are making errors.

The second type of study shows that perceptual learning leads to stable action. Wilson et al. (2010a) used a visual two alternative forced choice psychophysical judgment task to train observers to be able to perceive and discriminate 90° movement precisely. Before this strictly perceptual training, participants were unable to generate stable movement at 90°, but after having learned to see 90°, the participants were immediately able to control their movement to produce 90° coordination. Once they had learned to see it, they could do it. Wilson and Bingham (2008) then showed that certain perturbations of visually perceived movements affected the ability to perceive 90° coordination without affecting the ability to perceive 0° or 180° coordination. This confirmed that learning 90° involves learning to perceive different perceptual information than that used at 0° and 180°.

Rhythmic movement coordination and older adults

All the studies described thus far were performed with younger adults in their 20s. Much less is known about how older adults perform such tasks. Serrien et al. (2000) examined the stability and accuracy of the 0° and 180° relative phase patterns when performed by either younger (mean age 24) or older (mean age 75) adults. The participants performed in-phase and anti-phase cyclical extension movements with similar (i.e., two arms) and dissimilar (i.e., one leg and one arm) limbs. Phasing accuracy and relative phase variability did not differ between younger and older adults when using similar limbs, but deteriorated rapidly for the older adults using dissimilar limbs and more markedly for anti-phase than in-phase coordination. The authors suggested that this deterioration might have been a result of deficits in cognitive regulation and afferent information processing (i.e., perception) that come with advanced age.

Only two previous studies have investigated perceptuo-motor *learning* in older adults using such coordination tasks. Swinnen et al. (1998) investigated the learning capabilities of 9 young (mean age 19) and 9 older (mean age 73) adults, with participants producing 90° bimanual rhythmic movements of their forearms. Participants performed 50 15 s trials on each of two consecutive days and were given feedback about their performance (Lissajous displays during the trial, and post-trial relative motion information after every 5th trial). Participants moved so as to make a real-time plot of their movements line up with a circular reference shape. Thus, as in the Kovacs et al. (2009a, b) study, these participants were working with *transformed visual feedback* which makes the 90° task easier as long as the Lissajous information remains available. The problem with learning to produce a 90° coordination this way is that the learned performance transfers incompletely to performance using normal visual information, that is, just looking at your moving limbs. Transfer trials were administered at the start, in the middle, and at the end of each practice day and were also repeated 5 min and one week following the end of acquisition. These transfer trials were (in order) blindfolded, with normal vision and with Lissajous feedback. Participants also produced two trials of 0° and 180° before and after each session and at the end of the retention session. Results showed that, when trying to produce 90°, the young adults showed a large decrease in error on day 1, but this decrease was equivalent to that of the older adults on day 2. The older adults showed lower performance levels across acquisition and retention and were more variable overall. Swinnen et al. (1998) suggested that the lower performance of the older adults occurred because they were less able to avoid spontaneous transitions to 0° and 180° (cf. Zanone and Kelso 1992). They also suggested that this could be due in part to an inability to discover the correct pattern, that is, an inability to perceive 90°.

The second study of learning new rhythmic coordinations by older adults was performed by Wishart et al. (2002). In a pilot study, older and younger participants were required to produce a 90° bimanual coordination pattern while only using Lissajous displays during every 5th trial. While younger adults improved over time and sustained performance after practice, the older adults did not improve at all. Wishart et al. (2002) hypothesized that the amount of feedback information was not sufficient for the older adults to suppress the strong tendency to produce in-phase and anti-phase movements, and hence, they did not learn. As a result, the authors conducted a further study in which participants received either terminal feedback alone or both concurrent and terminal visual feedback after every trial during acquisition. In contrast to the pilot study, Wishart et al. (2002) now found that all of the older adults learned to perform 90° coordination, although still less well than the younger adults as shown by the fact they were less consistent. Both age groups benefitted from the concurrent visual feedback, although this occurred on day 1 for the young adults and not until the end of day 3 for the older adults. Similar to the Swinnen et al. (1998) study, the younger adults improved significantly over the first day, while the older adults made little improvement on day 1, but continued to improve over the next two days.

Feedback

Both Wishart et al. (2002) and Swinnen et al. (1998) used Lissajous feedback to train and also test their participants. For both age groups in the Swinnen et al. (1998) study, performance at post-test and retention was more successful when participants used Lissajous information than in other perceptual conditions (normal vision and blindfolded), and at retention, the group by condition interaction showed that the increase in relative phase error during the blindfolded and normal vision conditions was larger for the older then for the younger adults. The learning that occurred using Lissajous information transferred to other perceptual performance conditions less well for older than younger adults.

Lissajous displays change the perceptual information used in the task and thus limit the transfer of learned performance to other perceptual conditions, most importantly, to normal conditions in which a performer is simply viewing the actual rhythmic movements (e.g., Kovacs et al. 2009a, b; Leech and Wilson submitted). In a recent study, Wilson et al. (2010b) solved this problem by providing participants with online augmented feedback that did not replace the visual information normally available. Participants in a visual coordination task viewed two white dots moving horizontally on screen, one above the other, and their job was to control the bottom dot using a joystick to keep the dot in an instructed target phase relation with the other dot. When the participant was performing the task within 20° of the target relative phase, their dot would turn green. Participants given feedback (in the form of the dot turning green) were able to learn, while those who were not given this feedback were not. The advantage of this method was that once performance at 90° relative phase was learned, no special feedback was required to enable participants to continue performing at the newly learned level of performance. They could do it just looking at the motions themselves. In this study, all participants were young adults, so it is yet unknown how older adults would perform in the same task.

The current study

The existing research on learning new coordination patterns by older adults shows that older adults can learn to produce a 90° relative phase pattern in a bimanual coordination task when feedback is sufficient, although to a significantly lesser extent than their younger counterparts. However, unimanual coordination in older adults has yet to be examined, and the visual feedback used in the two existing studies consisted of Lissajous displays. These are known to make coordination at 90° much easier to perform with little practice (Kovacs et al. 2009a, b), but then performance transfers incompletely to conditions with only normal visual information available. Transforming the visual information about the success of their movements has consequences for what is learned, and we must therefore take a more explicitly perception–action approach to the question of how older adults learn skilled actions. There has also been no quantitative evaluation of the difference in learning rates between younger and older adults.

To fill this gap, we tested a group of younger adults in their 20s and two groups of older adults in their 70s and 80s on a visual coordination task in which they could see the rhythmic movements themselves plus a signal (the dots turning from white to green) telling them that they were performing the target coordination. Participants were tested on their baseline ability to move at 0°, 90°, and 180° then trained at 90° over 5 days of sessions. We then reevaluated their performance at post-test and retention. The data yielded learning curves that were fit by a model and used to estimate learning rates, separately for each of the three age groups (20s, 70s, 80s). Given the findings of Wishart et al. (2002) and Swinnen et al. (1998), we expected that the older adults would exhibit some learning to produce the novel (90°) coordination pattern, but that they would exhibit significantly lower perceptuo-motor learning rates than the younger participants.

Methods

Participants

Ten young adult participants in their 20s were recruited from the Indiana University community (3 male, 7 female; mean age 22). A further 17 older adults (nine 70 year olds (3 male, 6 female; mean age 74) and eight 80 year olds (2 male, 6 female; mean age 84)) were recruited from the wider community, resulting in a total of three groups: 20s, 70s, and 80s. All participants had normal or corrected-to-normal vision. At baseline, all participants performed below 50 % at 90° coordination and were better at performing 180° than 90° (when we averaged baseline performance). Measures of cognitive function were collected from the older adults using the Short Portable Mental Status Questionnaire (Pfeiffer 1975), and all participants scored within the range of normal mental functioning. The experiment was conducted with ethical approval from the local Ethics Committee.

Apparatus and procedure

Participants sat in front of a Dell Latitude 15″ laptop, with the monitor set to a resolution of 1,024 × 768 and a refresh rate of 60 Hz. A Logitech Force 3D Pro joystick was connected via USB to the PC. The joystick had its force feedback feature turned off, so there was no opposition to the participants' motion. The computer presented a display showing two dots, which were white on a black background, one above the other. The top dot was under the control of the computer, while the bottom dot was under the control of the participant via the joystick (all participants used their preferred hand). The amplitude of movement of each dot was 300 pixels, and each dot was 60 pixels in diameter; at the viewing distance of 70 cm this is ~7.5° visual angle. Stimulus presentation, data recording, and all data analysis were handled by a custom Matlab toolbox written by ADW, incorporating the Psychtoolbox (Brainard 1997; Kleiner et al. 2007; Pelli 1997; http://psychtoolbox.org).

There were four Assessment sessions (Baseline ×2, Post-Training and Retention) and five Training sessions. These were spread over eight separate days (not necessarily consecutive, but within a nine week period). We decided to do two baseline sessions and take the average to represent baseline performance. This was to ensure that (a) task novelty was not too large a contributing factor to baseline performance, and (b) second baseline scores that were better due to practice were similarly not used in isolation to represent pre-test performance. We elected to do multiple short training sessions rather than one long one to reduce the chances of fatigue affecting learning, and previous research has shown that distributed practice leads to superior performance compared to massed practice (see Donovan and Radosevich (1999) for a meta-analytic review).

In all sessions, the top dot was under the control of the computer. It oscillated from side to side at 0.75 Hz with amplitude ~7.5° visual angle, and each trial lasted 20 s. Participants moved the bottom dot from side to side using the joystick, attempting one of three target mean relative phases (0°, 90° or 180°). In the assessment sessions, participants viewed an 8 s demo of each target relative phase (0°, 180° or 90°) and then performed five trials of each, blocked and presented in that fixed order (total of 15 20 s trials). The first trial of each block was practice (with online feedback), and the data were not analyzed; there was no feedback for the four analyzed trials. In each of five training sessions, participants performed ten 20 s trials with a target mean relative phase of 90°, for a total of 50 trials over five separate days. An 8 s demo was shown before every trial. In each trial, online feedback was provided by changing the color of the person-controlled dot from white to green when the participant was moving at 90°, ± an error bandwidth. The error bandwidth was *faded* across sessions when performance reached a certain threshold. The level participants were started on in the first training session was dependent on performance in the baseline session: data were analyzed to see at which error bandwidth (from ±35° to ±10° in 2.5° intervals) the participant could perform the task 50 % of the time, and this was the level at which they started. After subsequent training sessions, data were again analyzed in a similar way, and if performance improved, the error bandwidth was altered for the next training session (but only by a maximum of 5° each time). If performance did not improve, the error bandwidth remained the same. Changes to the error bandwidth which drives learning was therefore self paced.

Participants were instructed to view the demo and then move at the indicated mean relative phase. They were additionally told that when the dot was green they were moving successfully. If the error bandwidth was different from that in the previous session, they were told this.

Data analysis

The two position time series from each trial were filtered using a low-pass Butterworth filter with a cut-off frequency of 10 Hz and numerically differentiated to yield a velocity time series. These were used to compute a time series of relative phase, the key measure of coordination between the two dots.

To assess the stability of the coordination over the course of a trial, we used *proportion of time on task* (PTT; see Wilson et al. 2010a, b). In human movement, stability is not independent of mean relative phase, so measures that simply assess overall movement variability (e.g., the standard deviation of mean relative phase or mean vector length) are confounded with the actual relative phase produced (see Wilson et al. 2005a and Snapp-Childs et al. 2011 for extensive analysis of this problem). Coordination stability at 90° can be artificially elevated if participants spend time at other locations (e.g., 0° or 180°), which they do as these locations are natural attractors (Zanone and Kelso 1992). Proportion of time on task allows us to address this problem. It is simply the proportion of the relative phase time series that falls within the range of the target phase ± a tolerance (e.g., of 20°), thus summarizing the data of interest (consistency and accuracy) and eliminating the confound. This measure ranges from 0 to 1, and validly measures stability of coordination at the required relative phase in a single number (Wilson et al. 2010a, b).

Results

All references to baseline performance refer to an average computed over the two baseline sessions. Figure 1 shows the performance of all groups at baseline, post-test, and retention across all conditions. Performance is measured as proportion of time on task, ±20°. The figure shows that all groups performed equally poorly at baseline for the 90° pattern, and the 20 year olds were only slightly better than the other two groups at performing 0° and 180° at baseline. All groups were better at performing 0° than 180° in all three sessions. For the 90° pattern, it is evident that the 20 year olds show a greater improvement between baseline and post-test than either of the other groups.

A 3-way mixed ANOVA was carried out with session (baseline, post-test and retention) and condition (0°, 180° and 90°) as within subjects variables, and group (20-year olds, 70-year olds, 80-year olds) as the between subjects variable. A significant main effect of group emerged [$F(1, 24) = 6.226$; $p < 0.01$, $\eta_p^2 = 0.34$] with the 20 year olds (mean = 0.58) performing better than the 70 year olds (mean = 0.46) and 80 year olds (mean = 0.46). A significant main effect of session was also identified

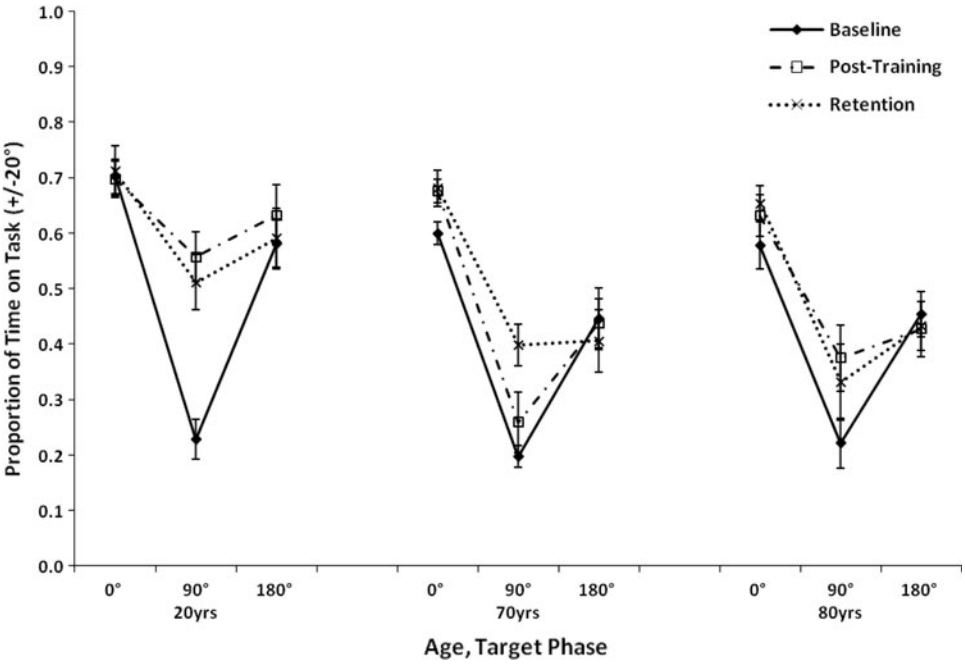

Fig. 1 Proportion of time spent within 20° of the target mean relative phase (0°, 90° and 180°) across the baseline (*solid line*), post-training (*dash-dot line*), and retention (*dotted line*) sessions for all three age groups. *Error bars* represent the standard error of the mean

[$F(2, 48) = 32.51$; $p < 0.001$, $\eta_p^2 = 0.58$] with performance at post-test (mean = 0.52) and retention (mean = 0.52) being better than performance at baseline (mean = 0.45). A significant main effect of condition was also found [$F(2,48) = 81.26$; $p < 0.001$, $\eta_p^2 = 0.77$] with performance at 0° (mean = 0.66) being better than performance at 180° (mean = 0.49) and 90° (mean = 0.34). Significant interactions were found between session and group [$F(4, 48) = 3.35$; $p < 0.05$, $\eta_p^2 = 0.22$] and session and condition [$F(4, 96) = 12.24$; $p < 0.001$, $\eta_p^2 = 0.34$], but not between condition and group. A significant 3-way interaction between group, session and condition was also identified [$F(8, 96) = 3.33$; $p < 0.01$, $\eta_p^2 = 0.22$], so further analyses were required to examine the data more thoroughly.

90°

Firstly, we wanted to determine whether older adults could learn the 90° relative phase pattern. Figure 2 shows the 90° performance at baseline, post-test, and retention by age. It is clear that the 20 year olds show a large increase in time on task between baseline and post-test that is not shown by the other groups.

A repeated measures ANOVA on the 90° performance data at baseline, post-test, and retention revealed a significant main effect of group [$F(1, 24) = 4.64$; $p < 0.05$, $\eta_p^2 = 0.28$] and a significant main effect of session [$F(2, 48) = 29.48$; $p < 0.001$, $\eta_p^2 = 0.55$]. There was also a significant group by session interaction [$F(2, 48) = 5.31$; $p < 0.01$, $\eta_p^2 = 0.31$].

To unpack the main effects and interactions, we examined paired samples *t* tests which show that there were significant improvements in performance at post-test compared to baseline for the twenty year olds [$t(9) = -7.34$; $p < 0.001$] and eighty year olds [$t(7) = -3.75$; $p < 0.01$], but not for the seventy year olds [$t(8) = -1.13$; $p = 0.29$]. However, examining baseline versus retention [$t(8) = -4.11$; $p < 0.01$] for the seventy year olds reveals significant improvement from baseline. No differences were found between post-test and retention conditions in separate tests for each age group.

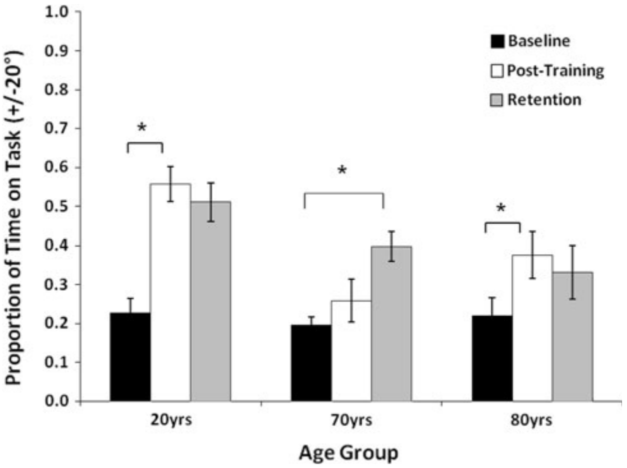

Fig. 2 Proportion of time spent within 20° of the 90° target mean relative phase across the baseline (*black bars*), post-training (*white bars*), and retention (*gray bars*) sessions for all three age groups. *Denotes a significant difference ($p < 0.05$). All groups showed improved performance at post-training or retention compared to baseline, but the younger adults showed a much greater difference. *Error bars* represent the standard error of the mean

Separate one-way ANOVAS and Bonferroni comparisons on the baseline and post-test data revealed no significant differences between any of the groups at baseline, but a significant difference between the twenty year olds and seventy year olds at post-test [$p < 0.01$] and marginally so between the twenty and eighty year olds [$p = 0.068$] (in both cases the twenty year olds performing better), but not between the seventy and eighty year olds [$p = 0.429$].

Learning rates for 90°

As well as examining potential differences in the amount of learning between baseline and post-test or retention, we also wanted to determine whether or not the learning *rates* between the groups were different and if so, then exactly how different. Figure 3 shows the mean learning curve for each of the three groups on the trained pattern of 90° relative phase across all sessions. Exponential functions were fitted to the data. The functions were of the form:

$$\mathrm{PTT} = a * \exp(-b/S), \qquad (1)$$

where PTT is "Proportion of Time on Task," S is session ($1 =$ baseline and $7 =$ post-test), and a and b are parameters. The function was fitted in three different ways, and results were compared to be sure they were essentially the same. First, the function was fit to the means separately for each age group using Quasi-Newton estimation in Systat 5.2. This yielded $r^2 = .99$ in all three cases. The values for parameter a were 0.664, 0.345, and 0.392, and for parameter b, they were 1.073, 0.536, and 0.584, respectively, for 20s, 70s, and 80s. Secondly, the PTT means and session numbers were transformed as follows:

$$\mathrm{PTT} \rightarrow \ln(\mathrm{PTT}) \quad \text{and} \quad S \rightarrow 1/S.$$

Least squares linear regression was used to fit a line to the relation between the two sets of transformed values, again separately for each group. The r^2 were .99, .66, and .93 for the 20s, 70s, and 80s, respectively. All were significant $p < 0.05$ or better.

Finally, this last approach was used again applied to the combined individual participant data for each group. However, in this last case, we also used multiple linear regression to test differences in slope, and intercept between the groups taken two at a time (Pedhazur 1982). The result of the comparison of 20s and 70s was significant ($p < 0.001$, $R^2 = 0.40$, $F(3,\ 129) = 29.0$), and both slope ($p < 0.005$, partial $F = 8.37$) and intercept ($p < 0.001$, partial $F = 38.19$) were different. The result of the comparison of 20s and 80s was significant ($p < 0.001$, $R^2 = 0.40$, $F(3,\ 125) = 26.5$), and both slope ($p < 0.05$, partial $F = 5.20$) and intercept ($p < 0.001$, partial $F = 24.96$) were different. Finally, the result of the comparison of 70s and 80s was significant ($p < 0.05$, $R^2 = 0.07$, $F(3,\ 114) = 3.0$), but neither slope ($p = .68$, partial $F = 0.17$) nor intercept ($p = .41$, partial $F = 0.68$) was different.

In the two sets of multiple linear regression analyses, the resulting linear equations were transformed back into the form of Eq. (1). The values found for the parameters a and b using all three approaches were essentially the same. Then, in each case, we computed the first derivative of the function in Eq. (1), that is:

$$(a * b)/S^2 * \exp(-b/S), \qquad (2)$$

and we evaluated this derivative at $S = 1$ to derive an estimate of the learning rate. Again, the resulting estimates were nearly identical using all three fitting methods. The resulting learning rates were 0.24 for 20 year olds, 0.10 for 70 year olds, and 0.12 for 80 year olds (reporting the mean of the results of the 3 methods in each case). The results of the multiple regression analysis showed that the learning

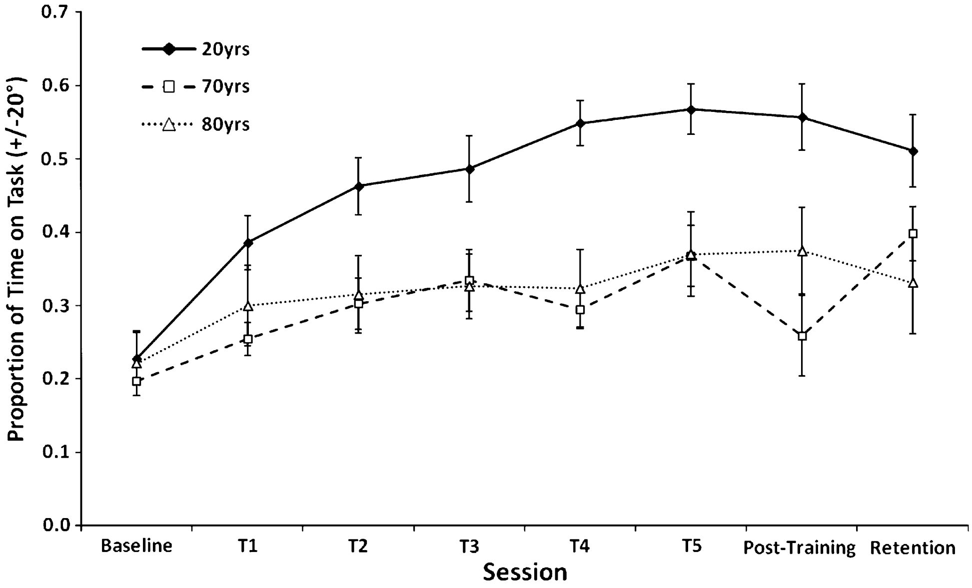

Fig. 3 Proportion of time on task for each age group across all sessions. *Error bars* represent the standard error of the mean

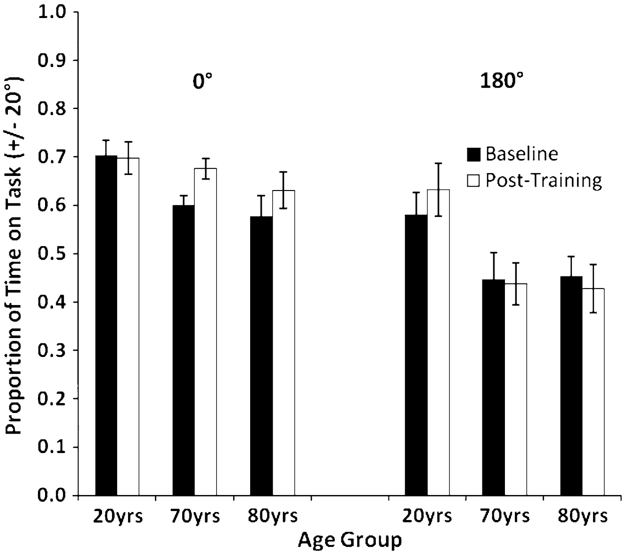

Fig. 4 Proportion of time spent within 20° of the target mean relative phase (0° and 180°) across the baseline (*black bars*) and post-training (*white bars*) sessions for all three age groups. Older adult performance was not significantly different from the younger adults at 0°, but this was not the case at 180°. *Error bars* represent the standard error of the mean

rate for the 20s was different from that for the 70s and 80s, while the latter two were not different from one another. The overall result was a finding that learning rates for older adults in their 70s or 80s were almost exactly half that for young adults in their 20s.

0° and 180°

We wanted to determine whether there were any changes in performance for the untrained coordination patterns, 0° and 180°, as a function of age group and/or training (at 90°). Learning 90° does not typically transfer to either 0° or 180°, because learning 90° entails learning a different perceptual coupling (Wilson and Bingham 2008). As shown in Fig. 4, there was an overall improvement from baseline to post-test in 0° performance. There was no significant group effect or interaction. This did not occur in 180° performance. Instead, 180° performance yielded a group difference, but no session effect and no interaction.

A repeated measures ANOVA on 0° performance revealed no significant main effect of group, but there was a significant main effect of session with performance being higher at post-test (mean = 0.668) than baseline (mean = 0.629) [$F(1, 24) = 6.511$; $p < 0.05$, $\eta_p^2 = 0.213$]. There was no interaction between group and session. There was no effect of group or interaction (both $p > 0.05$).

A repeated measures ANOVA on 180° performance revealed a significant main effect of group [$F(1, 24) = 4.51$; $p < 0.05$, $\eta_p^2 = 0.27$] with performance of the 20 year olds (mean = 0.607) being higher than that of the 70 year olds (mean = 0.442) and 80 year olds (mean = 0.442). There was no effect of session or interaction (again both $p > 0.05$).

Overall, therefore, all three age groups ended up equally able to perform 0° coordination. This shows that poorer performance by the older adults in the 90° conditions is not caused by any problems in using the joystick or seeing the display. However, the older adults were not as good as the younger participants at performing 180°. 0° is easy for a variety of reasons; the relative phase is clearly perceived (e.g., Wilson et al. 2005a), but also because it is effectively a tracking task. 180° is solely a coordination task, and performance depends on the perception of relative phase. In the present data, when the coordination increased in complexity, it affected performance, but only for the older adults. This suggests that the difference in learning rates seen at 90° may have something to do with the visual perception of relative phase.

Discussion

The purpose of this study was to investigate the rate of learning a novel coordinated rhythmic movement in older as compared to younger adults. Specifically, we tested whether or not older adults could learn to visually/unimanually produce a novel coordination pattern (90° relative phase) and measured learning rates for both younger and older adults to quantify any differences. Given previous findings (e.g., Wishart et al. 2002 and Swinnen et al. 1998), we predicted that although the older adults would show some evidence of learning, they would have more difficulty than the young adults and show a reduced rate of learning. The results were as predicted. We investigated learning and performance in older adults both in their 70s and in their 80s, but the results and the differences relative to the performance and learning in adults in their 20s were essentially the same. This lack of differences between the two older adult groups is interesting and perhaps unexpected. We don't believe this finding to be a result of sampling bias due to the fact that participants from both groups were recruited from the same places (local retirement home, tennis center, and local community). It might be the case that after the age of ~70, learning rate does not continue to decline, but evidence is needed to support this.

An exponential model of the learning fit the data well and returned estimates of learning rates that showed that those exhibited by the older adults where half (≈0.12) of those exhibited by younger adults (≈0.24). (Note: This 0.5 proportional relation between young and old in learning rates was also the same in comparison of the slopes from the linear fits to the transformed scores and in the relations between the respective *a* and *b* parameter values of the exponential functions.) This is indeed a substantial change, but also shows that older adults are still able to learn a new action skill. This is a very encouraging result! They also retained what they have learned equally well, at least, over the time interval measured in this study, ($\approx$1 week). Quantitative estimates of these changes in learning rates are important, because the learning curves and/or post-test results can give the impression that little or no learning occurs for older adults. This simply is not true.

What might underlie and produce the reliable differences in perceptuo-motor learning for younger and older adults that we have found? There are likely to be multiple factors, but our data allows us to suggest one that might be most significant in this task. We also tested performance, before and after training at 90° coordination, at both 0° and 180° coordination. We found that, as a result of the training, older adult performance of 0° coordination improved, but performance of 180° coordination did not. In addition, older adults (both in their 70s and 80s) were reliably worse in producing stable performance at 180° than were adults in their 20s. According to the Bingham model of this task (Bingham 2004a, b; Snapp-Childs et al. 2011), the difference in stability of performance between 0° and 180° is produced by differences in the speed differences between the two movements (empirically confirmed by Snapp-Childs et al. 2011). For example, for 0°, the dots move together and the relative speed difference is zero. For 180°, the relative speed difference varies over the cycle. At the end points, of course, the difference is 0° because momentarily they are not moving. Near the endpoints, the difference is small. However, at the mid-point of movement, at the point where both dots hit peak velocity and are moving in opposite directions, the speed difference is greatest and also the largest of any relative phase. Psychophysical studies of visual motion perception show that such speed differences condition the ability to see the relative directions of motion. The current results suggest that older observers are hit harder by this effect, which would then also impair learning at 90° which entails learning to perceptually discriminate and recognize this motion pattern. Indeed, research performed over the last decade has revealed visual motion perception deficits that emerge reliably with advanced aging (e.g., see Anderson (2012) for review). Older adults have been shown to have difficulties in visually discriminating differences in speed (Norman et al. 2003; Snowden and Kavanagh 2006) and in performing a wide variety of tasks involving motion perception (Ball and Sekuler 1986; Billino et al. 2008; Buckingham et al. 1987; Gilmore et al. 1992; Habak and Faubery 2000; Norman et al. 2000, 2003; Trick and Silverman 1991). This change seems to be underpinned by general changes in cortical function with age. For example, neuronal inhibition decreases with aging, and Betts et al. (2005) demonstrated that this leads to decreased center-surround antagonism in visual cortex and less finely resolved motion detection systems (see also Liang et al. 2010; Nedelko et al. 2010). These factors are bound to affect learning abilities for tasks that involve significant motion perception. The detailed interplay between such motion perception and motor learning in the context of aging should become an important focus for future investigations.

Conclusions

In summary, we have found that learning rates in a visual coordination task decrease significantly with advanced aging, but this decrease has only reduced the rates for adults in their 80s to about half what they are for people in their 20s. Learning therefore might just take a longer time and more practice. Programs for recovery from stroke and other conditions that affect older adults should therefore respect these reduced, but still effective learning rates for older adults. There are, of course, many practical limitations in terms of time and resources that must be overcome, so it remains to be seen whether this intact, but slower capacity to learn in older adults can benefit from manipulations of the training schedule known to improve the rate of learning (for instance, distributing practice). Further research is needed to determine exactly which factors are primarily responsible for the learning deficit. The current data suggests that while there are likely to be multiple factors at play, the deficits in motion perception that emerge with aging must remain a primary focus for future work.

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