Age-Related Loss of Adaptability to Fast Time Scales in Motor Variability

Jacob J. Sosnoff\textsuperscript{1} and Karl M. Newell\textsuperscript{2}

\textsuperscript{1}Department of Kinesiology and Community Health, University of Illinois at Urbana-Champaign. 
\textsuperscript{2}Department of Kinesiology, The Pennsylvania State University, University Park.

We investigated the ability of older adults to intentionally adapt their sensorimotor output to differing time and frequency properties (1/f noise structure) of a target-force target waveform. We tested the hypothesis that elderly adults are less adaptable than their younger counterparts to the time- and frequency-dependent demands of continuous sensorimotor output and that this effect is mediated by the frequency content of the task demand. The results showed that older adults were progressively less able than young adults to approximate the lighter-color-noise force targets and utilize the information in the higher frequencies of the target signal. There is a declining ability with aging to use the faster time scales of sensorimotor control, but the particular directional effect of the loss or gain of complexity of force output is moderated by the differential impact of task demands.

\textbf{Key Words:} Aging—Force variability—Adaptation—Time scales.

The organization of behavioral and physiological variability has been shown to be sensitive to the influences of healthy aging and the onset of degenerative diseases (Hultsch & McDonald, 2004; Lipsitz & Goldberger, 1992; MacDonald, Nyberg, & Backman, 2006; Newell, Vaillancourt, & Sosnoff, 2006; Vaillancourt & Newell, 2002). Decrement in sensorimotor function that occur with aging emerge from multiple factors at a variety of levels (Arking, 1998; Spirduso, 1995). Indeed, in many cases it is the interaction of multiple control systems that affects each particular marker of age (Lipsitz, 2002).

The reduced capacity to adapt to stress has been hypothesized to result from the loss of complexity with aging (Lipsitz & Goldberger, 1992). This hypothesis holds that the loss of complexity of a physiological control system results from either a reduction in the number of individual structural components (neurons, motor units, etc.) with advanced age or alterations in the coupling between these components. Although it has been over a decade since the loss of complexity theory of aging was introduced, there have been few examinations of the influence of aging on psychological phenomena from a complexity theory framework.

Nevertheless, there has been an increase in the examination of psychological processes with analytical tools associated with complexity and chaos theory (Gilden, Thornton, & Mallon, 1994; Gilden et al., 1995). This technique decomposes a time series and reveals the contribution of representative frequency components. Conceptually, each process contributing to the behavior has a unique frequency and the relative contribution of the process to the behavior is denoted by the amount of power at its characteristic frequency. For instance, in manual tracking performance dominated by visual motor processing, output results from visual motor processing about twice per second, that is, at 2 Hz, and to a much lesser extent physiological tremor at approximately 10 Hz (Poulton, 1974). A power spectral analysis of such sensorimotor behavior would reveal a dominant peak (i.e., large amount of power) at 2 Hz and a smaller peak at 10 Hz.

The log-log plot of the power spectrum (i.e., log power vs log frequency) provides an index of the how the power, $P$, changes as a function of frequency, that is, spectral or beta slope, and informs about the interaction (i.e., correlation) of underlying processes (Bassingthwaighte et al., 1994). It is characterized by the equation $P(f) = 1/f^b$. If there is no change in power as a function of frequency, then the spectral slope ($b$) is zero and there is no interaction between processes; this is known as white noise. In contrast, if the spectral slope is relatively steeper (e.g., has an exponent of $-2$), such as in brown noise, then the variations in the behavioral output are due to a few dominant processes, with other processes providing relatively smaller contributions to the output. Pink noise has a spectral slope of $-1$ and is characterized as a mixture of interaction and noninteraction between processes.

In this dynamical systems framework to aging, it has been proposed that age-related differences in the complexity of human perceptual motor output depend on the constraints to action (Newell & Vaillancourt, 2001; Newell et al., 2006; Vaillancourt & Newell, 2002). In this view, the original loss of complexity hypothesis (Lipsitz & Goldberger, 1992) reflects the consequences of a general and relatively slow time-scale

A primary analytical technique to examine 1/f processes is power spectral analysis (Bassingthwaighte, Liebovitch, & West, 1994; Gilden et al., 1995). This technique decomposes a time series and reveals the contribution of representative frequency components. Conceptually, each process contributing to the behavior has a unique frequency and the relative contribution of the process to the behavior is denoted by the amount of power at its characteristic frequency. For instance, in manual tracking performance dominated by visual motor processing, output results from visual motor processing about twice per second, that is, at 2 Hz, and to a much lesser extent physiological tremor at approximately 10 Hz (Poulton, 1974). A power spectral analysis of such sensorimotor behavior would reveal a dominant peak (i.e., large amount of power) at 2 Hz and a smaller peak at 10 Hz.

The log-log plot of the power spectrum (i.e., log power vs log frequency) provides an index of the how the power, $P$, changes as a function of frequency, that is, spectral or beta slope, and informs about the interaction (i.e., correlation) of underlying processes (Bassingthwaighte et al., 1994). It is characterized by the equation $P(f) = 1/f^b$. If there is no change in power as a function of frequency, then the spectral slope ($b$) is zero and there is no interaction between processes; this is known as white noise. In contrast, if the spectral slope is relatively steeper (e.g., has an exponent of $-2$), such as in brown noise, then the variations in the behavioral output are due to a few dominant processes, with other processes providing relatively smaller contributions to the output. Pink noise has a spectral slope of $-1$ and is characterized as a mixture of interaction and noninteraction between processes.

In this dynamical systems framework to aging, it has been proposed that age-related differences in the complexity of human perceptual motor output depend on the constraints to action (Newell & Vaillancourt, 2001; Newell et al., 2006; Vaillancourt & Newell, 2002). In this view, the original loss of complexity hypothesis (Lipsitz & Goldberger, 1992) reflects the consequences of a general and relatively slow time-scale
aging effect that also serves as the background to faster time-scale task-induced changes in complexity as a function of aging. Vaillancourt and Newell proposed that aging leads to a difficulty in adapting behavior to particular task demands, whether it is increasing or decreasing the complexity of behavior or the number of active degrees of freedom (individual components) that are regulated in movement. The lack of adaptation demonstrated by older adults in their output is consistent with but not the same as the differentiation hypothesis of advanced age (Baltes & Lindenberger, 1997).

Preliminary evidence has supported this loss of adaptability view to aging. Vaillancourt and Newell (2003) showed that age-related differences in the complexity of sensorimotor output depend on the intrinsic dynamics of the task. That is, when a task demand was realized that required an increase in dynamical degrees of freedom from the intrinsic dynamics, aging led to a loss of complexity. However, when the task goal required a reduction in the dynamical degrees of freedom of the motor output, aging was associated with an increase in complexity (Vaillancourt, Sosnoff, & Newell, 2004). A limitation of these previous experiments is that, a priori, it is often not clear what tasks will require more or less complexity in motor output to achieve the task goal. One way around this ambiguity is to have the task goal as a particular target output that can vary in dynamical properties that are specified a priori.

Our purpose in the current investigation was to test the hypothesis that elderly adults are less adaptable than their younger counterparts to the time-dependent demands of continuous force output. We expected aging to reduce the capacity to adaptively change the task-relevant $1/f$ properties of the force dynamics. We hypothesized that there would be a progressive loss of complexity indicated by lower approximate entropy values and steeper spectral slopes with aging in motor output to the less-time-dependent waveforms (i.e., white and pink noise), but greater complexity indicated by higher approximate entropy values and lower spectral slopes as the target signal becomes more time dependent (i.e., brown- and black-noise waveforms). We also hypothesized that in motor output to the white- and pink-noise force waveforms there would be a more adaptable output (increased approximate entropy and lower steep spectral slope) as the frequency content of the target waveforms included a greater number of higher frequencies and that this ability to scale motor output with frequency content would be reduced in older adults.

**Methods**

**Participants**

A total of 25 right-hand-dominant individuals participated in the study and were divided into groups based on age. The young group (18 to 29 years of age) consisted of 12 healthy individuals (6 women and 6 men) with a mean age of 22.7 years ($SD = 3.7$). The old group consisted of 13 individuals (6 women and 7 men) ranging from in age from 65 to 69 years, with a mean age of 67.9 years ($SD = 1.3$). All participants were free of neuromuscular disorders, diabetes, and orthopedic abnormalities of the fingers, wrist, or hand, and all had normal or corrected-to-normal vision. Each participant provided informed consent and the procedures were approved by the Penn State Institutional Review Board. One participant from the old group failed to comply with instructions and was removed from our subsequent analysis.

**Apparatus**

We used the same experimental setup that Sosnoff and Newell (2006a) used. Briefly, participants sat facing a computer monitor and produced isometric force against a load cell. The load cell measures compressive forces produced by the finger.

We sampled the force signal at 140 Hz. The smallest increment of change in force that we could measure was .0016 N. Prior to being saved on the hard drive of the computer, the force signal was passed through an eighth- pole Butterworth low-pass filter (858L8B-1, Frequency Devices, Inc.) with a cutoff frequency of 25.6 Hz. At each sampling interval, the produced force was presented on the monitor.

**Procedures**

**Estimation of maximal voluntary contraction.**—Once informed consent was granted, we determined each participant’s maximal voluntary contraction (MVC) strength. We instructed each participant to produce the maximal amount of isometric force possible by abducting his or her index finger. The participant produced maximal force while pressing against the load cell. The force applied to the load cell was displayed on the monitor to provide visual feedback. Three 6-s maximal contractions were recorded, with 30 s of rest between each contraction. We determined the participant’s MVC to be the highest force produced over the three trials.

**Experimental design and instructions.**—The participants adjusted their force output to match a red target line displayed on the monitor, and they viewed online feedback of their performance in the form of a series of yellow dots that corresponded to the force trajectory. The force trace moved left to right across the screen with time. We experimentally manipulated the force target so that it would take one of six distinct waveforms. Each waveform was characterized by a unique fractal dimension. The waveforms were as follows: (a) straight line (i.e., constant force); (b) 1-Hz sine wave; (c) white Gaussian noise; (d) pink noise; (e) brown noise; and (f) black noise (see Figure 1). The mean amplitude of each force target was 10% of the participants’ MVC. In addition, we varied the frequency content of the $1/f$ force signals from 0 to 4 Hz, from 0 to 8 Hz, and from 0 to 12 Hz (see Figure 2). We did not manipulate the frequency content of the constant and sinusoidal target.

The testing session consisted of six blocks of trials. Four of the blocks consisted of one of the four noise waveforms and the three frequency bandwidths (12 trials). The remaining two blocks consisted of the constant or sine-wave target (3 trials each). Participants completed three 20-s trials at each unique condition, resulting in a total of 42. The blocks were randomly presented within the testing session and the order of the frequency bandwidths was presented randomly within each block. All three trials of a unique noise waveform–frequency content condition were completed serially. In order to minimize fatigue, participants were given a 30-s rest between trials and a 1-min rest between blocks. We instructed the participants to
minimize the deviations between the yellow trajectory and the target line throughout all trials.

**Data Analysis**

We removed the initial 4 s and final 1 s of force data from each trial prior to analysis to avoid the initial force stabilization or premature cessation of force production. We performed all data processing by using software written in Version 7 of Matlab (The Mathworks, Inc.).

**Task performance.** — In order to access task performance as a function of target waveform and frequency content, we calculated the root mean square error (RMSE) of the force data for each trial.

**Structure of force output.** — To examine if participants were able to modulate the structure of their force output to explicit task demands, we examined the structure of the force output in the time domain. We assessed the time-domain structure of force output by means of approximate entropy (Pincus, 1991). Approximate entropy yields a single value that quantifies the regularity (complexity) of a time series. This measure obtains the repetition of vectors of length $m$ and $m + 1$ that repeat within a tolerance range of $r$ of the standard deviation of the time series. The approximated entropy ($m = 2, r = 0.2$) of a time series, $X$, is calculated as the natural logarithm of the ratio of the count of recurring vectors of length $m$ against that of $m + 1$. Higher values of the approximate entropy represent greater irregularity within the time series, whereas lower values represent higher regularity in the time series. Increases in approximate entropy have been interpreted as an increase in the signal’s time-domain complexity (Pincus).

We computed the power spectrum by using the SPECTRUM command in Matlab 7.0 that uses Welch’s averaged periodogram method. We used a 256-point nonoverlapping Hanning window, with a sampling frequency of 140 Hz; this resulted in a 0.55-Hz bin width. The power in each bin represented the amplitude of force oscillations that occur at the frequency specified by the bin. We calculated the changes in power as a function of force target in two distinct ways. First, we calculated the proportion of power in 4-Hz bandwidths from 0 to 4 Hz, 0 to 8 Hz, and 0 to 12 Hz. This frequency range accounted for approximately 99% of the power within the spectrum. Second, we performed a linear regression on the log$_{10}$-transformed spectral profile within this 0- to 12-Hz frequency range. The slope of this regression function identifies the rate of change of spectral power as a function of spectral frequency within a spectral profile (Gilden et al., 1995). For the purposes of the present experiment, only the scope is of interest, and as the power spectrum becomes more broadband, the value of scope will increase from negative values toward zero.

**Statistical analysis.** — The average of the last two trials of each of the dependent variables just discussed were each...
placed independently in a three-way ($2 \times 4 \times 3$) repeated-measures analysis of variance (ANOVA), with waveform and frequency content as within-subject factors and age as the between-subjects factor. When relevant, we used Tukey’s Honestly Significant Difference test to determine the specific effects contributing to the general ANOVA. We conducted a two-way ANOVA with age as a between-group factor and task (constant–sinusoidal) as a between-subjects factor to examine age differences in the production of force in these boundary conditions. To further examine whether constant or rhythmical force output was different from the force output at any of the $1/f$ target waveforms, we conducted independent-sample $t$ tests. We utilized Bonferroni corrections to account for the multiple comparisons. We evaluated all statistics as significant when there was less than a 5% chance of making a Type I error ($p < .05$), and we report only significant effects here. We completed all statistical analyses by using the SPSS statistical package (SPSS, Inc). We report the dependent values as means unless otherwise noted.

**RESULTS**

**Root Mean Square Error**

Task performance as indexed by RMSE is shown in Figure 3. A three-way (Age $\times$ Waveform $\times$ Frequency) repeated-measures
ANOVA showed a main effect for age, $F(1, 24) = 2.63, p < .05, \eta^2 = .11$, and waveform, $F(3, 72) = 5.49, p < .05, \eta^2 = .18$. Our post hoc analysis revealed that the older age group (0.525 N) had greater RMSE than did the younger age group (0.385 N). We also found that the black-noise waveform had significantly less error than the other waveforms did (black, 0.271 N; white, 0.524 N; pink, 0.548 N; and brown, 0.476 N).

A comparison between constant and sinusoidal force output revealed that the constant-force production had a lower RMSE (0.10) than did the sinusoidal force output (0.583): $F(1, 22) = 213, p < .05, \eta^2 = .91$. Overall, we found that the constant-force output had a lower amount of RMSE than all noise waveforms ($p < .05$). The rhythmical force output had greater error than the force output to the black-noise target ($p < .05$).

Approximate Entropy

Figure 4 shows the mean approximate entropy of the force output as a function of age, $1/f$ target waveform, and the frequency bandwidth. Our statistical analysis revealed a main effect for waveform, $F(3, 54) = 66.15, p < .05, \eta^2 = .79$, and frequency bandwidth, $F(2, 36) = 5.42, p < .05, \eta^2 = .23$. Our post hoc analysis revealed that approximate entropy decreased with darkening of the waveform (white, .361; pink, .283; brown, .177; and black, .130). In contrast, force output increased irregularity with increases in frequency content from .225 in the 0- to 4-Hz waveforms to .250 in the 0- to 12-Hz waveforms.

We observed several interactions: Waveform $\times$ Frequency, $F(6, 108) = 3.66, p < .05, \eta^2 = .17$; Waveform $\times$ Age, $F(3, 54) = 23.2, p < .05, \eta^2 = .56$; Frequency Content $\times$ Age, $F(2, 36) = 3.36, p < .05, \eta^2 = .16$; and Age $\times$ Waveform $\times$ Frequency.
Frequency Content, $F(6, 108) = 3.67, p < .05, \eta^2 = .17$. Our post hoc analysis revealed that the interaction between waveform and frequency content resulted from an increase in approximate entropy in the output to the white- and pink-noise waveforms as frequency content increased, but no change in the output to the brown- and black-noise waveforms. The interaction between age and waveform resulted from the young adults having greater approximate entropy than the older adults in the white- and pink-noise waveforms (.457 and .358 vs .265 and .208, respectively), but less approximate entropy than the older adults in the brown and black waveforms (.163 and .100 vs .191 and .151, respectively). The Age × Frequency Content interaction resulted from the old adults not modifying their output with increases in frequency content, whereas the young adults did. The triple interaction between age, waveform, and frequency content resulted from the older adults displaying greater approximate entropy than the young adults in their output to the brown-noise waveform only with 0- to 8-Hz and 0- to 12-Hz frequency content (0.19 and 0.20 vs 0.161 and .168, respectively).

Our comparison between constant and sinusoidal force output revealed that constant-force production had greater approximate entropy (.43) than sinusoidal force output (.19): $F(1, 22) = 90.2, p < .05, \eta^2 = .80$. An Age × Task interaction, $F(1, 22) = 90.2, p < .05, \eta^2 = .80$, was a result of the young adults (.47) having greater approximate entropy than the older adults (.38) in the constant-force production task, but less approximate entropy in the sinusoidal task (.16 vs .21, respectively).

In order to examine whether constant or rhythmical force output was different from the force output to any of the waveforms and if the difference was age dependent, we conducted independent-sample $t$ tests in each age group. For both age groups there was no significant difference ($p > .05$) between the irregularity of constant-force output to that of force output to a white-noise waveform. Constant-force output did have greater irregularity than output to the 4-Hz and 8-Hz pink-, brown-, and black-noise waveforms in both age groups. The only age difference was that there was no significant difference in approximate entropy in the 12-Hz pink-noise waveform and constant-force target for the young age group, whereas the older group had greater approximate entropy in constant-force output.

There was a greater effect of age on the difference between the irregularity (i.e., approximate entropy) of sinusoidal force output and that of the output to the noise waveforms. The younger adults had greater approximate entropy in force output to the pink-noise waveforms than sinusoidal force output, whereas there was no difference for the older adults. Both age groups had greater approximate entropy in output to the white-noise waveforms than sinusoidal force output. There was no difference between output to brown-noise waveforms and sinusoidal output in both groups. In contrast, there was greater irregularity in sinusoidal force output than in the output to the black-noise waveforms in both age groups.

Spectral Slope

Figure 5 shows that the spectral slope was affected by age, waveform, and frequency content. A three-way ANOVA (Age × Waveform × Frequency Content) revealed main effects for waveform, $F(3, 54) = 8.69, p < .05, \eta^2 = .28$, and frequency bandwidth, $F(2, 36) = 3.09, p < .05, \eta^2 = .12$. Our post hoc analysis revealed that spectral slope decreased with darkening of the waveform (white, −2.26; pink, −2.49; brown, −2.66; and black, −2.54). In contrast, force output increased spectral slope with increases in frequency content from −2.55 in the 0- to 4-Hz waveforms to −2.41 in the 0- to 12-Hz waveforms.

We also observed two-way interactions between waveform and age, $F(1, 23) = 7.8, p < .05, \eta^2 = .25$, and waveform and frequency, $F(6, 132) = 3.6, p < .05, \eta^2 = .14$. Our post hoc analysis revealed that the interaction between waveform and age resulted from the young adults having steeper spectral slopes in the white-noise (−2.13) and pink-noise (−2.42) waveforms than the older adults (−2.39 and −2.56, respectively), but no difference between groups in the brown-noise (young, −2.69; old, −2.63) or black-noise (young, −2.51; old, −2.49) waveforms. The Waveform × Frequency Content interaction resulted from there being an increase (less negative) in spectral slope in output to the white- and pink-noise waveforms with increase in frequency content, but no change in the brown- and black-noise waveforms.

Proportion of Power

Our statistical analysis of proportion of power (POP) in the 0- to 4-Hz bandwidth revealed main effects for waveform, $F(3, 54) = 12.1, p < .05, \eta^2 = .34$, and frequency bandwidth, $F(2, 36) = 2.84, p < .05, \eta^2 = .11$. Our post hoc analysis revealed that force output to the white-noise waveform (.879) had lower POP$_{0–4\,\text{Hz}}$ than output to the other waveforms (pink, .936; brown, .956; and black, .937). Force output to waveforms with 0- to 4-Hz frequency content (.935) had greater POP$_{0–4\,\text{Hz}}$ than those with 0- to 8-Hz content (.919).

There was a two-way interaction between waveform and age, $F(3, 54) = 3.12, p < .05, \eta^2 = .12$, and waveform and frequency content, $F(6, 132) = 3.4, p < .05, \eta^2 = .13$. The interaction between waveform and age resulted from the young adult group having less POP$_{0–4\,\text{Hz}}$ in force output to the white- and pink-noise waveforms (.868 and .915) than the old age group (.891 and .957), but greater POP$_{0–4\,\text{Hz}}$ in the brown- and black-noise waveforms (.969 and .949 vs .944 and .926, respectively). The interaction between waveform and frequency content was found to be due to a decrease in POP$_{0–4\,\text{Hz}}$ in the white-noise waveform with an increase of frequency content (.911, .856, and .870), but no significant changes with the other waveforms. Force output to the constant target resulted in POP$_{0–4\,\text{Hz}}$ (.893), which was similar to that of the white- and pink-noise waveforms. In contrast, force output to the sinusoidal force output had POP$_{0–4\,\text{Hz}}$ (.985), which was similar to the brown- and black-noise waveforms.

Our analysis of POP$_{4.8\,\text{Hz}}$ revealed main effects for waveform, $F(3, 54) = 5.85, p < .05, \eta^2 = .21$, and frequency bandwidth, $F(2, 36) = 4.95, p < .05, \eta^2 = .18$. Our post hoc analysis revealed that force output to the white-noise waveform had significantly greater POP$_{4.8\,\text{Hz}}$ (.108) than the other waveforms (pink, .052; brown, .048; and black, .061). Force output to waveforms with 0- to 4-Hz frequency content had less POP$_{4.8\,\text{Hz}}$ (.055) than the waveforms with higher frequency content (0–8 Hz, .076; 0–12 Hz, .071).
We also noted an interaction between waveform and frequency content, $F(6, 132) = 3.8, p < .05, \eta^2 = .15$, in the analysis of $\text{POP}_{4-8 \text{ Hz}}$. The interaction resulted because there was an increase in $\text{POP}_{4-8 \text{ Hz}}$ with increase in frequency content in force output to the white- and pink-noise waveform (.067 vs .137 and .043 vs .057, respectively), but no change in $\text{POP}_{4-8 \text{ Hz}}$ in the black- and brown-noise waveforms with changes in frequency content. Force output to the constant target resulted in $\text{POP}_{4-8 \text{ Hz}} (.091)$, which was similar to that of the white-noise waveforms. In contrast, force output to the sinusoidal force output had $\text{POP}_{4-8 \text{ Hz}} (.013)$, which was less than the other waveforms.

Our analysis of $\text{POP}_{8-12 \text{ Hz}}$ showed a two-way interaction between waveform and frequency content, $F(6, 132) = 2.7, p < .05, \eta^2 = .11$. Our post hoc analysis revealed that there was an increase in $\text{POP}_{8-12 \text{ Hz}}$ with increase in frequency content only in force output to the white-noise waveform (.007 to .013). Force output to the constant target resulted in $\text{POP}_{8-12 \text{ Hz}} (.091)$, which was similar to that of the white-noise waveforms. In contrast, force output to the sinusoidal force output had $\text{POP}_{8-12 \text{ Hz}} (.013)$, which was less than the other waveforms.

**DISCUSSION**

We set up the experiment to test the hypothesis that elderly adults are less adaptable than their younger counterparts to the time-dependent demands of continuous isometric force output, and that this effect is mediated by the frequency content of the force-time task demands. The hypothesis is grounded in the perspectives of the loss of complexity in aging (Lipsitz & Goldberger, 1992) and the loss of adaptability in aging to task constraints (Vaillancourt & Newell, 2002). In the loss of adaptation view of aging, there is both the influence of a long (slow) time-scale change to behavior with advancing age and a short (fast) time-scale influence to aging-related changes in the organization of motor output and performance outcome.

The findings clearly showed that the direction of the age-related differences in the complexity of force output is task
dependent (Newell & Vaillancourt, 2001; Vaillancourt & Newell, 2002, 2003). In the constant-force-level task the older adults showed reduced complexity, whereas in the sine-wave task the older adults showed enhanced complexity of force output (Vaillancourt & Newell, 2003). As we anticipated, RMSE was inversely related to complexity in the constant-force task but directly related in the sine-wave task. This age-related task-mediated effect is consistent with the proposition that aging reduces the potential of the sensorimotor system to adapt to task demands. In the force tasks studied here, the constant level of force output required an increment of complexity from the intrinsic dynamics to reduce error, and, in contrast in the sine-wave task, a reduction of complexity to reduce error.

The findings in the 1/f color-noise force targets provide complementary evidence for the task-mediated effects of aging on the complexity of force output. In the white- and pink-noise force targets, only the younger adults were able to increase the complexity of force output to the enhanced frequency content of the force signal. The older adults showed no difference in the complexity of force output across the different task demands of the lighter-noise force targets. Thus, only the younger adults were able to adaptively use the faster time-scale information in the force target. This finding is compatible with the established tendency for slowness in movement preparation and execution with aging (Hartley, 2006; Salthouse, 1985), but it is in the context of behavioral complexity that is mediated by the task-dependent interaction of feedforward and feedback processes (Desmurget & Grafton, 2000; Slikitin, Vaillancourt, & Newell, 2000; Sosnoff & Newell, 2005).

Although it is intuitive to suggest that the age-related decrease in the use of faster time scales of information results from a decrease in processing speed (Salthouse, 1985), there is minimal evidence to support this claim. In an investigation examining whether age-related differences in force control resulted from an age-related increase in the time required to perceive and correct for a motor error, older adults were found to have longer motor-error correction speeds, but there was no relation between correction speed and the amount or structure of force variability (Sosnoff & Newell, 2006a). It was speculated that older adults compensate for a decrease in processing speed by emphasizing other control processes. The current investigation illustrates that this compensatory strategy results in a decreased ability for older adults to adapt their output to varying task demands (i.e., increasing frequency content).

In the darker brown and black force targets neither the younger nor the older age group showed the capacity to use the faster time-scale information in the force output. This is because the force targets in the darker noise conditions are dominated by slow time scales that lead to an enhanced regular sinusoidal force output. Nevertheless, it is interesting that the older age group produced a more complex force output in the brown- and black-noise targets in a manner consistent with their performance in the perfectly rhythmical sine-wave force output. Thus, the age-related capacity to selectively exploit the fast time-scale information in the force target is task dependent. The lack of adaptability of sensorimotor performance seen in older adults is congruent with the predictions of the det differentiation hypothesis of life-span psychology (Baltes & Lindenberger, 1997).

It has been proposed that 1/f properties result from the interaction of multiple psychological and physiological processes (Kello et al., 2007). It is logical to speculate that, in the current investigation, the processes driving 1/f properties in motor output most likely pertain to feedback and feedforward sensorimotor mechanisms (Sosnoff & Newell, 2005). The lack of adaptability observed in the older adults in the current experiment suggests that there is reduced ability to alter the interaction between contributing processes.

Finally, it should be noted that this experiment shows in effect the adaptive range of age-related force control to 1/f force targets. Here the participants were required to intentionally produce a 1/f force output, as opposed to recent findings in which a 1/f variation in reaction time was found in laboratory cognitive tasks (Gilden, 1997, 2001; Van Orden, Holden, & Turvey, 2003). The findings are clear in showing that there is a declining ability to use the faster time scales of control in aging, but the particular directional effect of the loss or gain of complexity is moderated by the differential impact of task demands (Newell et al., 2006; Vaillancourt & Newell, 2002).

REFERENCES


