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The Effect of Aging on Adaptive Eye-Hand Coordination

Jinhua Guan and Michael G. Wade

School of Kinesiology and Leisure Studies, University of Minnesota—Twin Cities.

Perceptual-motor adaptability of older adults (65 and older) was assessed. Participants in two groups (younger, 20–36 years, and older, 67–87 years) pointed 100 times at a straight-ahead visual target while looking through laterally displacing prisms, with the hand visible early in the pointing movement. Aftereffect tests were administered after adaptation. Each group was then split into decay and readaptation subgroups in which respective treatments were given twice. After each treatment, aftereffect tests were readministered. Eye-hand total shift was significantly smaller for older participants, proprioceptive shift was not statistically smaller for older participants, and visual shift did not appear. Readaptation produced greater reduction in aftereffects than did decay; this effect was the same for both groups. The main conclusion is that perceptual-motor adaptability declines with advancing age.

IT is not surprising that profound changes occur in the human perceptual-motor system with advancing age. Declines in the visual, proprioceptive, motor, and central nervous systems have been documented in earlier studies (Bondareff, 1985; Fozard, 1990; Kenshalo, 1977; Spirduso & MacRae, 1990). As an important perceptual-motor function, eye-hand coordination is not spared from the effects of aging; examples of age-related modifications of this function include delays in reaction time and movement time, decreased accuracy in reaching–aiming movement, decreased steadiness in the nonpreferred hand, decreased manual dexterity, and reduced speed in writing digits and words (Birren & Botwinick, 1951; Chaput & Proteau, 1996; Miles, 1931; Welford, 1977). Because these studies focused on age-related changes in eye-hand coordination under undistorted visual conditions, their scope is limited. Human eye-hand coordination is characterized by a remarkable ability to adapt to sensory modifications (Held & Freedman, 1963; Welch, 1978). When exposed to an optical distortion, individuals quickly readjust their eye-hand coordinative patterns and function normally under such a new visual environment. Such adaptability has been documented in a plethora of studies on prism adaptation (Harris, 1963; Hay & Pick, 1966; Held & Hein, 1958; Helmholtz, 1925; Redding & Wallace, 1993). However, because the majority of studies were conducted on younger adults, it is not clear whether principles thus derived can directly extrapolate to older adults (aged 65 and over). To date, little information is available about how aging may affect adaptability of the perceptual-motor system.

When a person views the displaced image of the hand reaching for an object, he or she at first misses the object by pointing in the direction of the prism displacement. After some practice, the person adapts and reaches more accurately. However, after the prism is removed, he or she misses by pointing to the side opposite the prism displacement. Despite the apparent ease in performance, research over the last 100 years has revealed the enormous complexity of such adaptive properties of the perceptual-motor system. Theories on prism adaptation have largely focused on two considerations: (a) the nature (i.e., mechanisms) of prism adaptation, and (b) conditions under which adaptation occurs, namely, which conditions lead to which end-states of adaptation (Redding & Wallace, 1997; Welch, 1978). The model proposed by Redding and Wallace (1988a, 1988b, 1993, 1996, 1997) has adequately addressed both of these theoretical considerations.

Redding and Wallace (1988a, 1988b, 1993, 1996, 1997) argued that the perceptual-motor system (e.g., eye-hand, ear-hand, and eye-foot) can be conceptualized as consisting of multiple sensorimotor systems (e.g., eye-head, ear-neck, hand-shoulder, and foot-trunk). Each sensorimotor system has an effector, sensors, and control structures and can function independently of other sensorimotor system(s). There are two kinds of sensors: exteroceptor, which provides information about events in the outside world, and proprioceptor, which provides information about the behavioral status of the sensorimotor system itself. When operating independently, a sensorimotor system executes tasks specific to itself. For example, during quiet reading, the eye-head system functions without the involvement of other sensorimotor systems. However, when a task requires a more integrated response, two or more sensorimotor systems can be linked in a coordinated fashion to achieve the performance goal. The nature of such a linkage is hierarchical: one system guides and the other is guided. But the direction of guidance may be reversed. For example, when a person reaches for a cup, the eye guides the hand to the target; the direction of guidance is eye-to-hand. Alternately, when a person reads a wristwatch, the hand guides the eye; the direction of guidance becomes hand-to-eye (Redding & Wallace, 1997).

Organization of such a perceptual-motor system requires two distinct processes: spatial alignment and strategic perceptual-motor control. Spatial alignment ensures that the sensory space of an exteroceptor matches the motor space of an effector with its proprioceptive sensor, within a sensorimotor system and between sensorimotor systems. Such a matching function is performed in noetic space, a spatial representation common to all sensorimotor systems (Redding & Wallace, 1997). Examples of alignment include spatial mappings of eye-retina onto head, wrist onto forearm, forearm onto upper arm, forearm onto shoulder, head onto trunk, and leg onto trunk. Strategic perceptual-motor control is "the class of motor control processes that normally enable common action (coordination) of various sensorimotor systems that serve perceptual-motor behavior" (Redding & Wallace, 1996, p. 379). Strategic control has available a variety of strategies, including feedforward and feedback control, knowledge of results compensation, and associative feedforward learning (for details, see Redding & Wallace, 1997). These strategies are used to correct for performance error induced by spatial misalignment of sensorimotor systems in a strategic linkage.

Spatial alignment is subject to a variety of perturbations such as natural cell death, growth, and pathology, and prism adaptation may be considered as an experimental example of such perturbations (Redding & Wallace, 1988a, 1988b, 1993, 1996). When prism-induced distortion is introduced in a perceptual-motor task, the sensory and motor spaces no longer transform into the same representation in noetic space. Thus, misalignment is detected and a parametric readjustment of spatial relations is subsequently performed to realign the sensorimotor systems. According to Redding and Wallace (1997), such realignment occurs in the sensory (exteroceptive or proprioceptive) structure of the guided system. In addition to spatial realignment, adaptive change may also occur in strategic control. Such change occurs between sensorimotor systems without adaptive change in individual sensorimotor systems. Strategic control assumes the role of higher level processes that monitor and, if necessary, intervene in coordinative linkage of sensorimotor systems (Redding & Wallace, 1997). One example of its intervening function is to deliberately specify positions for the guided system that do not match target positions as indicated by the guiding system. With practice, a person may adapt to the new mapping even with incomplete spatial realignment. For example, during prism exposure, instead of pointing at a position where a target appears to be, a person may choose to point at a position to the side of the target where the finger is expected to be at the target when it comes into view. Over successive trials, such a side-pointing strategy may become so solidified as to become a part of the adaptive behavior (Redding & Wallace, 1997).

Aside from the mechanisms of adaptation, the Redding and Wallace (1988a, 1988b, 1993, 1996, 1997) model can also predict which conditions lead to which end-states of adaptation. As described previously, sensorimotor systems are strategically linked; one system guides, and the other is guided. When misalignment occurs, the input from the guided system is discrepant with the output from the guiding system. The solution is to realign the guided system so that it agrees with the guiding system; thus, realignment occurs in the guided system. In sagittal pointing movements, the availability of visual feedback and the duration of limb movement codetermine the direction of guidance and the localization of subsequent realignment (Redding & Wallace, 1988a, 1988b, 1992, 1994). With early visual feedback (concurrent exposure), the direction of guidance is eye-to-hand; realignment occurs in the hand-head proprioceptive system. Alternately, with late visual feedback (terminal exposure) the direction of guidance is hand-to-eye; realignment occurs in the eye-head visual system (Redding & Wallace, 1988a, 1988b). In addition, when movement duration is short (e.g., 1 s), realignment occurs in the head-hand proprioceptive system regardless of the visual feedback condition. As movement time increases, realignment in the eye-head visual system increases as that in the head-hand proprioceptive system decreases (Redding & Wallace, 1994). The gradual shift in the localization of realignment from the eye-head visual system to the head-hand proprioceptive system is contingent on a graded change in visual feedback and/or movement duration (Redding & Wallace, 1992, 1994).

Both strategic perceptual-motor control and spatial realignment can be assessed experimentally. Performance during prism exposure represents contributions of both strategic perceptual-motor control and spatial realignment; before and after exposure changes (aftereffects) reflect spatial realignment, and the difference between performance and aftereffects reflects strategic perceptual-motor control (Redding & Wallace, 1997).

Eye-hand coordination system can be analyzed into two component systems: head-hand proprioceptive system and eye-head visual system. Aftereffect of the eye-hand system is referred to as *total shift* (TS) or *negative aftereffect*; aftereffects of the head-hand and eye-head systems are referred to as *proprioceptive shift* (PS) and *visual shift* (VS), respectively. Previous studies indicated that the algebraic sum of changes in head-hand (PS) and eye-head (VS) component systems are equal to changes in eye-hand (TS) system (Hay & Pick, 1966; McLaughlin, Rifkin, & Webster, 1966; Wallace, 1977; Wilkinson, 1971). This two-component view provides direct evidence for the additivity hypothesis, which assumes that total adaptive changes are the simple sum of adaptive changes at different loci of bodily articulations (Hamilton, 1964; Harris, 1965). However, when prism exposure involves target pointing where error feedback is available, TS can exceed the algebraic sum of PS and VS (Choe & Welch, 1974; Redding & Wallace, 1988b, 1994; Templeton, Howard & Wilkinson, 1974; Welch, 1974; Welch, Choe, & Heinrich, 1974). This phenomenon has been known as underadditivity of adaptation, which reflects a transfer to TS aftereffect from strategic control (Redding & Wallace, 1988b, 1994, 1997).

Spontaneous attenuation of prism aftereffects, also known as decay, may occur if participants rest in darkness or with eyes closed for a period of time following prism removal. In essence, decay represents the ability of the perceptual-motor system to reinstate normal coordinative patterns in the absence of any visual feedback (Hamilton & Bossom, 1964). Spontaneous decay is a negatively accelerated function (Redding, 1973, 1975; Welch, 1978). Decay of lateral displacement was complete after 56 min in darkness (Redding, 1975). The rate of decay seems to depend on the availability of visual feedback. With late visual feedback (i.e., terminal exposure), adaptation is more resistant to decay than with early visual feedback, namely, concurrent exposure (Welch, 1978).

In addition to spontaneous decay, readaptation may be used to attenuate prism aftereffects. In this procedure, participants watch the hand movements with prism removed. Few studies have compared the rates of decay and readaptation under the lateral displacement condition. Hamilton and Bossom (1964) reported that both decay and readaptation led to significant reduction in aftereffects over a period of 15 min and that readaptation was not more effective than decay in such reduction. However, Welch, Bleam, and Needham (unpublished 1970 study, cited in Welch, 1978) found that readaptation led to significant reduction in prism aftereffects, whereas decay produced little reduction over a period of 10 min. Because so few studies have pursued this issue, a conclusion seems impossible. There has been at least one report that the rate of readaptation was faster than that of decay under optical tilt condition (Ebenholtz, 1968). However, one should avoid a direct comparison of decay and readaptation when different optical distortions (i.e., optical tilts and lateral displacement) are involved. Redding (1973, 1975) reported that tilt and displacement appear to involve two different processes and show different characteristics of decay.

Adaptive eye-hand coordination is a specific human behavior. Birren (1959) argued that age-related changes in behavior result to some extent from alterations in the biological properties of the nervous system and to some extent from interference of past habits of the nervous system. Instances of biological changes include loss of neurons, accumulation of lipofuscin, neurofibrillary tangles, granuovascuolar degeneration, senile plaques, and reduction in blood supply to the brain (Scheibel, 1996; Whitbourne, 1986). These biological events have broad functional implications, including reduced abilities in sensation, perception, memory, learning, and decision making (Whitbourne, 1986). Over the years, regions of the brain critical for prism adaptation have been identified; such regions include the prefrontal cortex, caudate nucleus, posterior parietal cortex, and cerebellum (Baizer & Glickstern, 1973, 1994; Bossom, 1965, 1972; Clower et al., 1996). The cerebellum was found to experience age-related loss of Purkinje cells (Bondareff, 1985; Scheibel, 1996). Because Purkinje cells are the primary source of outflow from the cerebellar cortex, the loss of these cells must affect many cerebellum-modulated neural processes (Scheibel, 1996). The caudate nucleus is part of a pathway linking substantial nigra and striatum. Age-related degeneration of this pathway is reflected by a severe decline in dopamine activity accompanied by a corresponding loss of substantia nigra neurons (Bondareff, 1985; Scheibel, 1996). The decrease of dopamine, when severe, causes Parkinson's disease, a neurological disorder associated with motor disturbances (Whitbourne, 1986). Despite these evidences, we are not aware of any study that has focused on aging of the brain and prism adaptation.

Habits of the nervous system refer to the consolidation of perceptual-motor organization as a result of experience or learning. It is plausible that with advancing age there is an increased interference from past habits with present learning (Birren, 1964). For instance, when a perceptual-motor task requires complex spatial transpositions, performance of older adults deteriorates disproportionately in both speed and accuracy (Welford, 1977). Such deterioration in spatial transposition may be interpreted as indicating that aging is correlated with a greater likelihood of interference from normal spatial relations with transposed spatial relations. Similarly, we argue that with advancing age there may be an increased likelihood of interference from past perceptual-motor habits under undistorted visual conditions with the acquisition of perceptual-motor mappings under distorted visual conditions. In other words, the perceptual-motor habits formed over a lifetime may lead to a reduced level of perceptual-motor adaptability.

Our primary purpose in this study was to assess the effect of aging on adaptive eye-hand coordination. Specifically, we documented the following aspects of the adaptive behavior: (a) the rate and extent of prism adaptation, (b) the sensory (visual and proprioceptive) contributions to prism adaptation, and (c) the rate and extent of decay or readaptation of aftereffects. On a deeper level of analysis, we intended to: (a) determine the localization of decline in adaptive eye-hand coordination (i.e., whether such decline is due to change in spatial realignment or decrease in strategic perceptual-motor control) and (b) determine the etiology of decline in adaptive eye-hand coordination (i.e., whether such decline results from biological changes of the perceptual-motor system, interference of past perceptual-motor habits, or combined effects of both). We argue that the localization of decline can be determined by looking at possible age-related differences in underadditivity of adaptation. Because underadditivity reflects the amount of transfer to TS by strategic control, an age-related lack, or even a reduced level, of underadditivity would indicate a change in strategic control. On the other hand, an equal amount of underadditivity between the two age groups would indicate no age-related decline in strategic control. Thus, any age-related decline in adaptive eye-hand coordination must be attributed to spatial realignment. Similarly, we argue that the etiology of decline can be determined by comparing the rate of decay of aftereffects between older and younger adults. Decay of aftereffects reflects the ability of an adapted system to return to normal perceptual-motor relations. If the decline is due to biological changes of the perceptual-motor system, older adults will show a slower return of normal eye-hand coordination. Alternately, if the decline is due to interference from past perceptual-motor habits, older participants will show a faster return of normal eye-hand coordination. Our secondary purpose in the present investigation was to assess the effect of aging on eye-hand coordination under undistorted visual conditions. Specifically, we documented (a) response accuracy and (b) response variability in eye-hand, head-hand, and eye-head systems.

METHOD

Participants

Twenty-one younger (aged 20–36 years, $M = 26 \pm 5$ years) and 21 older (aged 67–87 years, $M = 76 \pm 6$ years) right-handed adults took part in this experiment. The older participants were community residents in a major midwestern metropolitan area, who were recruited through senior community centers. The younger participants were undergraduate and graduate students at a university in the same region. The older participants were randomly assigned to two reductive treatment subgroups—11 in the decay subgroup (5 men and 6 women) and 10 in the readaptation subgroup (5 men and 5 women). Then, the number of older participants in each treatment subgroup was matched by an equal number of younger participants. There were 5 men and 6 women in the younger decay subgroup and 5 men and 5 women in the younger readaptation subgroup. All participants had corrected or uncorrected normal vision. None had any neurological or movement-related disorders or used any psychotic drugs.

Apparatus

The apparatus was a custom-made table (100 cm wide × 60 cm deep × 140 cm high) sprayed flat black (Figure 1). A plank (50 cm high × 60 cm wide) flanked each side of the table. On the interior of the planks, hooked screws were mounted to allow a visual occluder, a piece of black fabric covered with Colortron foam on both sides, to hang over the table surface. (Black Colortron foam is a nonreflective material that functions to reduce light reflection that may disturb data collection by the infrared-based WATSMART system. This material, manufactured by the American Foam Corp. of Rhode Island, was supplied by Northern Digital, Inc., 403 Albert Street, Waterloo, Ontario, Canada N2L 3V2.) The occluder hung with a slight slant toward the participant: 35 cm above the table surface on the participant's side and 45 cm on the opposite side (i.e., on the front). Mounted to the front of the table was an arched screen-like frame, in which five wooden dowels (50 cm in height × 2 cm in diameter) were put in a vertical orientation. These dowels, labeled "1" through "5" clockwise from the participant's perspective, were placed at −18°, −10°, 0°, 11°, and 22° relative to the participant's midbody axis that ran from the head to the trunk in a sitting posture; the dowels served as visual targets.

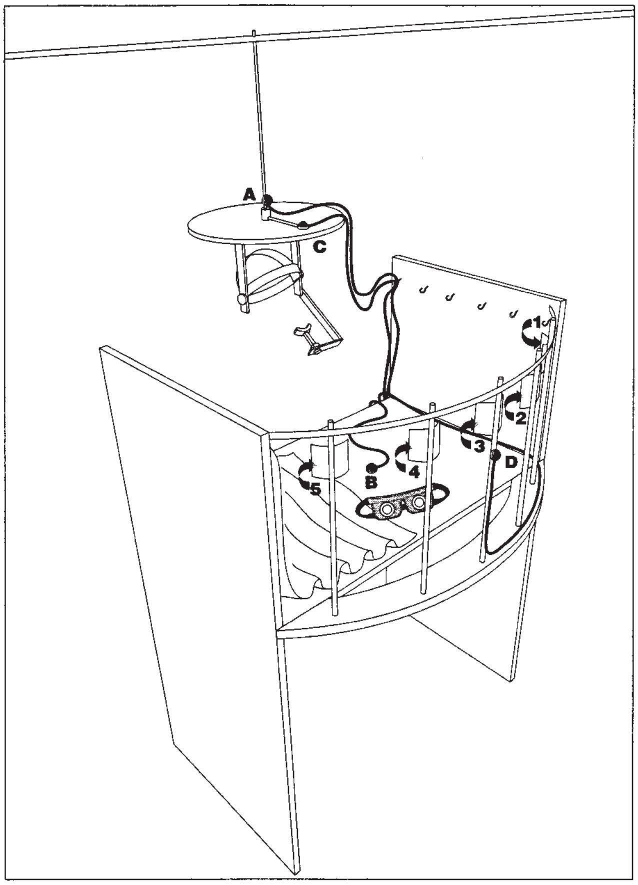

Figure 1. Apparatus. Participants were seated, with head restrained by the headpiece suspended from above, and wore welder's goggles with a wedge prism mounted in each eyepiece. There were four infared markers, labeled A–D, and five visual targets, labeled 1–5. The Colortron-covered fabric draping down the side panel of the table was a visual occluder, which hung over the table surface during the eye-hand test.

A structure resembling a pull-up bar (255 cm high × 230 cm wide) was placed over the participant's head. Suspended from the middle of the horizontal bar was a vertically oriented bar, whose lower end was connected to a headpiece. This headpiece was made of a rectangular iron frame (25 cm long × 21 cm wide × 2.5 cm deep) that resembled an ordinary picture frame with its bottom side open. A welder's cap, mounted to the interior of the frame, could be moved up and down relative to the frame to accommodate the participant's sitting height; the experimenter could adjust the size of the cap by turning a knob at its back. The frame was connected, at the top, to the vertical bar by a washer and could rotate freely in the transverse plane unless it was locked. A stick-like pointer, attached to the washer at one end and pointed outward horizontally, was in alignment with the participant's nose and turned with the head. A piece of cardboard located over the participant's head blocked the view of the pointer. A dental bite-piece was installed in the lower part of the headpiece for the participant to bite on. A pair of welder's goggles with a 20-diopter wedge prism mounted to each eyepiece was used for inducing optical distortion. Set based-left or based-right, these prisms shifted the line of sight to either side by 11.3° if worn over the eyes. The frame of the welder's goggles was opaque so that when the participant wore the goggles he or she could see outside only through the prisms, which allowed a 60° binocular visual field. Another pair of welder's goggles with plain glass mounted to each eyepiece was used during the coordination tests.

Four WATSMART infrared markers were used in the measurement of movement. Marker A, placed on the lower end of the vertical bar, indicated the position of the midbody axis; this marker remained stationary throughout the experiment and served as the origin of a two-dimensional (2-D) coordinate system that corresponded to the transverse plain. Marker B, attached to the tip of the middle finger of the participant's right hand, signaled the position of the hand relative to the midbody axis. Marker C, attached to the tip of the pointer over the participant's head, signaled the orientation of the head relative to the midbody axis. Marker D, attached to Target 3 (which was located straight ahead of the participant), served as a reference for the placement of the test table. Two WATSMART cameras, mounted securely on tripods (210 cm high), were angled 60° downward and 45°

inward toward the recording area. The distance from each of the cameras to the center of the recording area was about 300 cm; the average root mean squared error during calibration of the system was 2.14; and the volume of the recording area was 125 cm wide, 125 cm deep, and 100 cm high. Data were collected by the WATSMART system at a sampling frequency of 30 Hz for a period of 4 s during each trial. The experimenter initiated data collection by striking the "Return" key on a computer keyboard. An internal clock in the computer controlled the length of the collection and terminated the collection at the end of 4 s.

This experiment was conducted in a windowless office-turned laboratory (4.2 m wide × 4.8 m deep × 3.1 m high). To reduce light reflections, we covered the ceiling and walls with Colortron foam and covered the floor with plywood sprayed flat black. Two 100-watt fluorescent lights, suspended from the ceiling, illuminated the laboratory.

Design

We used a doubly multivariate repeated-measures design for the purpose of statistical analysis. This design was a mixture of two between-subject variables (age and reductive treatment) and two within-subject variables (experimental phase and localization). Of the two within-subject variables, the experimental phase was a repeated-measures variable and consisted of (a) preadaptation, (b) adaptation, (c) Reduction 1, and (d) Reduction 2. The other within-subject variable, localization, consisted of three loci of adaptation: (a) eye-hand system, (b) head-hand proprioceptive system, and (c) eye-head visual system. Of the between-subject variables, age consisted of a younger adult group and an older adult group. The other between-subject variable (i.e., reductive treatment) consisted of a decay subgroup and a readaptation subgroup. Together, the two between-subject variables made up the following four age–treatment subgroups: (a) older decay, (b) older readaptation, (c) younger decay, and (d) younger readaptation. Because the reductive treatment was not applied to the participants until Reduction 1, age was the only between-subject variable during the preadaptation and adaptation phases.

Procedure

Upon arrival in the laboratory, the participant was asked to fill out a consent form and a questionnaire on his or her health status. Then, the experimenter checked the participant's visual acuity with a Snellen eye chart and the range of motion in the neck and in the right shoulder. For visual acuity, the criterion was 20/40 uncorrected or corrected vision; for neck mobility, the criterion was a 45° head rotation to the left or to the right of the body's midline; for shoulder mobility, the criterion was a fully extended and horizontally positioned right arm rotating 90° to the right and 45° to the left of the body's midline. No participants were eliminated on the basis of these tests.

Preadaptation phase.—Before the experiment began, the experimenter instructed each participant about the procedures, including information about the four experimental phases (i.e., preadaptation, adaptation, Reduction 1 and Reduction 2), but he did not reveal the purposes of these procedures. He also explained to the participant the optical properties of the prism-mounted goggles and the plain glass goggles.

After these instructions, the participant was seated at the test table. The height of the chair on which he or she sat was adjusted so that he or she could rest the forearm comfortably on the table surface. The participant placed the head inside the headpiece and bit on the dental bite-piece. The experimenter adjusted the size of the welder's cap so that it fitted snugly around the participant's head. If necessary, he also adjusted the vertical position of the cap relative to the headpiece to accommodate the participant's sitting height. Once the headpiece was tightened, the participant could no longer move the head independently of the headpiece. The head position remained fixed (i.e., facing straight ahead) for most of the experiment, except for when the headpiece was unlocked, during eye-head and head-hand tests, to allow head rotation to the left or to the right. Then, the experimenter taped Marker B to the tip of the middle finger of the participant's right hand and told the participant to put this hand on the table and by the upper abdomen in anticipation of the preexposure tests.

After these preliminary preparations, the experiment began. The participant was given three preexposure tests (i.e., eye-hand, head-hand, and eye-head). These preexposure tests allowed us to assess age-related changes in coordination under undistorted visual conditions and provided baseline values for prism adaptation. We subtracted these baseline values from corresponding postexposure–postreduction values to obtain prism aftereffects.

In the eye-hand preexposure test, the experimenter hung the occluder over the table surface so that the participant could not see his or her own hand or arm moving beneath the occluder. Wearing the plain glass goggles, the participant was instructed to look at the visual target selected by the experimenter, reach out and point at the target with the right hand, and then draw the hand back. The pointing movement was performed with all five fingers fully extended and the thumb at the top. During the entire eye-hand test, the head position was fixed facing straight ahead. The participant was told to move the hand out and back in 4 s and was given three practice trials each with verbal feedback provided on movement time. During the actual test, no more verbal feedback was provided; the participant relied on him- or herself in the control of movement time. As soon as the participant's right arm started to reach out, the experimenter started data collection by striking the "Return" key on a computer keyboard. The eye-hand preexposure test consisted of 10 trials—2 for each of the five visual targets. The presentation of the visual targets was randomized by a pseudo-randomization procedure.

In the head-hand preexposure test, the experimenter unlocked the headpiece so that the participant could turn the head to the left or to the right. The participant was instructed to close the eyes and slowly turn the head to one side until he or she was told to stop. The experimenter decided where the head should stop on an arbitrary basis. But he made sure that each stop was at a different location (usually once left and once right) and within 25° left or right of the participant's midbody axis. The participant was told to reach out with the right hand in the direction as indicated by his or her nose and then draw the hand back. He or she was told to move the hand out and back in 4 s and was given three practice trials each with verbal feedback provided on movement time. During the actual test, no more verbal feedback was provided; the participant relied on him- or herself in the control of movement time. As soon as the participant's right hand started to reach out, the experimenter activated the WATSMART system to start data collection. The head-hand preexposure test was given five times.

In the eye-head preexposure test, the experimenter unlocked the headpiece if it remained locked. He selected a visual target based on a randomized sequence and read out the number of the target to the participant. Upon receiving a command to move, the participant turned the head, faced the designated target directly, and stayed there until he or she was told he or she could move. Once the participant indicated by a verbal report that he or she believed he or she was facing the designated target directly, the experimenter activated the WATSMART system to start data collection. The eye-head preexposure test was given 10 times—twice for each of the five visual targets. Finally, the presentation of the eye-hand, head-hand, and eye-head preexposure tests was also randomized by a pseudo-randomization procedure.

Adaptation phase.—The adaptation phase of the experiment consisted of a prism exposure period and a postexposure test period. During the prism exposure period, the visual occluder was removed so that the participant could view the hand early in the pointing movements (early visual feedback). The participant's head was fixed facing straight ahead. He or she wore a pair of 20-diopter prism goggles that laterally displaced the visual field by 11.3°; one half of the participants donned based-left prisms and the other half based-right. The participant could not see the hand at its resting position because the opaque frame of the prism goggles blocked the view. But as soon as the hand started to reach out (about one third of the total pointing movement), he or she could see the hand. Each participant performed 100 right-handed pointing movements at Target 3, which was located straight ahead. A distributed practice schedule was used. The 100 movements were broken down into five blocks of 20 movements and there was a 30-s interval between trial blocks during which the participant simply rested with eyes closed. The participant was instructed to move the hand out and back in 4 s. Verbal feedback on movement time was provided after each block of trials. During the postexposure tests, the experimenter replaced the prism-mounted goggles with the plain glass goggles and gave the participant three postexposure tests. These postexposure tests, identical to the preexposure tests, were intended to measure postexposure coordination in eye-hand, head-hand, and eye-head systems. The before and after exposure changes (i.e., the TS, PS, and VS aftereffects) were taken to represent prism adaptation. All three postexposure tests consisted of five trials; in the eye-hand and eye-head tests, there was one trial for each visual target. These visual targets were randomly presented using a pseudo-randomization procedure.

Reduction phases.—Each of the two reduction phases consisted of a reductive treatment period and a postreduction test period. During these two phases, each age group was split into a decay subgroup and a readaptation subgroup. Each participant in the decay subgroup closed the eyes, rested quietly for 5 min and took three postreduction tests immediately after the rest. These postreduction tests, identical to the pre- and postexposure tests, were administered for the purpose of providing a measure of reduction in prism aftereffects. The differences between preexposure and postreduction coordination tests were taken to represent the residual adaptive changes (i.e., the residual TS, PS, and VS aftereffects), the extent of adaptation that remains after a period of reductive treatment. By contrast, each participant in the readaptation subgroup was instructed to put on the plain glass goggles and point, with the right hand, at Target 3 for five blocks of 10 movements and, after each block, rested quietly with eyes closed for 20 s. The duration of the readaptation treatment was 5 min, which was comparable to the duration of the decay treatment the other subgroup received. Immediately after this treatment, the participant took three postreduction tests that were identical to the pre- and the postexposure tests administered during earlier phases of the experiment. All postreduction tests consisted of five trials. In the eye-hand and eye-head tests, there was one trial for each visual target. These visual targets were randomly presented using a pseudo-randomization procedure. Reduction 2 was simply a repetition of Reduction 1.

Data Analysis

Initial preparation.—The data were in two-dimensional positions when collected initially: left-right and up-down. Using a direct linear transform algorithm, we reconstructed the two dimensions of the each infrared marker into three dimensions (left-right, near-far, and up-down). Then, the three-dimensional data were smoothed out by a second-order Butterworth filter with a cutoff frequency of 6 Hz. After the filtering procedure, the up-down dimension was excluded from further analysis because the current experiment focused on movements in the left-right and near-far dimensions.

Positions of the hand and head.—The positions of the hand and head were expressed in angular values in a coordinate system with Marker A as the origin. The WATSMART system collected 120 instantaneous angular values for each of the four markers used during a trial. Calculations were somewhat different for the eye-hand, head-hand, and eye-head tests. For the eye-hand test, we selected a single value of the hand position at the terminus of its reach (i.e., when the distance between Markers A and B was at a maximum) out of the 120 instantaneous values to represent the orientation of the hand. For the head-hand test, both a single value of the hand position at the terminus of its reach and a corresponding value of the head position at that particular instant were selected, and the difference between the two values was taken to represent the head-hand response. For eye-head test, the angular position of the head relative to the mid-body axis when the head turned to a certain direction was recorded. Because the head was not in motion during data collection and the standard deviation of the 120 instantaneous values was very small (less than 0.20), a mean of these values was taken to represent the orientation of the head.

Extent and variability of the TS, PS, and VS aftereffects.—To calculate the TS aftereffect, we subtracted the preexposure values of the eye-hand test from the postexposure–postreduction values of the same test, resulting in a distribution of difference values. The extent of TS aftereffect was the average of these difference values. Calculations of the extent of PS and VS aftereffects were identical. The adaptive direction of the TS and PS aftereffects was opposite to the prism displacement, whereas the adaptive direction of the VS aftereffect was the same as the prism displacement. Response variability of the TS aftereffect was based on the variable error of these difference values. The variable error was calculated by using the formula

$$\text{Variable error} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n}},$$

where x_i is the difference score on Trial i, $\bar{x}$ is the mean of the difference scores, and n is the number of trials. Calculations of response variability in the PS and VS aftereffects were identical.

Accuracy and variability in preexposure responses.—For eye-hand and eye-head tests, the preexposure responses were subtracted from the corresponding target positions. For the head-hand test, the preexposure responses of the hand were subtracted from the corresponding responses of the head. These subtractions resulted in a distribution of difference values for each test. Response accuracy in any system was the average of the absolute difference values in that particular system. Response variability in any system was the variable error of the difference values in that particular system.

Statistical analysis.—Data were analyzed in four major steps. The first step focused on the adaptation phase of the experiment. In this step, the effect of aging on the extent of adaptation and on response variability of adaptation was assessed. The second step focused on the two reduction phases. In this step, the extent of within-subject reduction of adaptation and the effects of aging and/or reductive treatment (i.e., decay and readaptation) on the reduction of adaptation were assessed. The third step focused on the analysis of additivity. In this step, the extent of TS aftereffect and the algebraic sum of PS and VS aftereffects were assessed. The fourth step assessed age-related changes in response accuracy and variability during the preexposure phase.

RESULTS

Adaptation Phase

Aging and the extent of adaptation.—Table 1 shows the extent of TS, PS, and VS in the younger and older adult groups. These data were submitted to a two-group multivariate analysis of variance (MANOVA; two-sample Hotelling's T^2) with TS, PS, and VS as dependent variables. The results from this analysis indicated that the extent of adaptation was significantly greater in the younger group than in the older group when TS, PS, and VS were considered together, $F(3,38) = 5.90$, $p < .01$. But this age-related difference was limited to TS alone, $F(1,40) = 18.62$, $p < .01$. PS and VS did not show any age-related decline when considered either alone or together, PS, $F(1,40) = 1.18$, $p > .05$; VS, $F(1,40) = 0.50$, $p > .05$; PS + VS, $F(1,40) = 1.53$, $p > .05$. We interpreted these results to mean that adaptive eye-hand coordination as indicated by the TS aftereffect declines with advancing age.

Table 1 also shows that the adaptation occurred primarily in the eye-hand and head-hand systems and that there was little or no adaptation in the eye-head system. To be qualified as reliable adaptive changes, the extent of these changes must be statistically greater than zero. To assess if these adaptive changes were reliable, we individually submitted data from the older and the younger adult groups to a one-group MANOVA (one-sample Hotelling's T^2). Results from the analysis of the older adult group indicated that the combined effect of TS, PS, and VS was significantly different from zero, $F(3,18) = 19.32$, $p < .01$. However, this effect was limited to TS, $F(1,20) = 61.50$, $p < .01$, and PS, $F(1,20) = 11.01$, $p < .01$. VS was not significantly different from zero, $F(1,20) = 0.28$, $p > .05$. Results from the analysis of the younger adult group were similar. The combined effect of TS, PS, and VS was significantly different from zero, $F(3,18) = 78.16$, $p < .01$. However, this effect was limited to TS, $F(1,20) = 212.58$, $p < .01$, and PS, $F(1,20) = 30.18$, $p < .01$. VS was not significantly different from zero, $F(1,20) = 0.23$, $p > .05$. Thus, both the older and younger adult groups showed reliable adaptive changes in the eye-hand and head-hand systems, although not in the eye-head system.

Aging and response variability in prism adaptation.—Table 2 shows that the older and younger groups were comparable in response variability in TS ($M_1 - M_2 = -0.26$), PS ($M_1 - M_2 = -0.27$), and VS ($M_1 - M_2 = -0.89$). These data were submitted to a two-group MANOVA (two-sample Hotelling's T^2) with TS, PS, and VS as dependent variables. The results from this analysis indicated that there was no age-related difference when TS, PS, and VS were considered together, $F(3,38) = 2.40$, $p > .05$. Given that the two age groups were different in the extent of TS, we interpreted the lack of age-related increase in response variabil-

Table 1. Extent of Total Shift (TS), Proprioceptive Shift (PS), and Visual Shift (VS), in Degrees, During the Adaptation Phase

	Younger (n = 21)		Older (n = 21)		Difference
Aftereffect	M_1	SD_1	M_2	SD_2	($M_1 - M_2$)
TS	4.92	1.55	2.80	1.64	2.12
PS	3.49	2.91	2.43	3.36	1.06
VS	0.15	1.46	−0.26	2.29	NA[a]

[a]The age-related difference in VS was not calculated because VS in the older adult group was in the antiadaptive direction.

Table 2. Response Variability in Total Shift (TS), Proprioceptive Shift (PS), and Visual Shift (VS), in Degrees, During the Adaptation Phase

	Younger (n = 21)		Older (n = 21)		
Aftereffect	M_1	SD_1	M_2	SD_2	Difference ($M_1 - M_2$)
TS	1.35	0.76	1.61	0.84	−0.26
PS	3.34	1.87	3.61	1.91	−0.27
VS	1.82	0.89	2.71	1.44	−0.89

ity of adaptation as indicating that adaptability is independent of variability.

Reduction Phases

Within-subject reduction of adaptation.—Figure 2 shows that readaptation led to substantial within-subject reduction in TS and PS during the reduction phases. This reduction was evident in both age groups. In contrast, decay led to little within-subject reduction during the same reduction phases. In addition, VS showed within-subject reduction in neither reduction phase. Data obtained under all age and treatment conditions and under all experimental phases were submitted to a MANOVA. Structurally, this analysis had two between-subject variables (age and reductive treatment) and two within-subject variables (experimental phase and localization). Of the two within-subject variables, the experimental phase was a repeated-measures variable.

Results from this analysis indicated that the extent of adaptation decreased as a function of experimental phase, $F(6,33) = 13.87$, $p < .01$. Within-subject reduction of adaptation did not depend on age, $F(6,33) = 0.71$, $p > .05$. But the magnitude of this reduction depended on the specific reductive treatment (i.e., decay or readaptation), $F(6,33) = 2.74$, $p < .05$. A breakdown of the interaction between reductive treatment and experimental phase indicated that the two readaptation subgroups showed a significant within-subject reduction of adaptation, $F(6,14) = 11.58$, $p < .01$, whereas the two decay subgroups showed little or no within-subject reduction, $F(6,16) = 2.26$, $p > .05$. Further analysis indicated that readaptation led to significant within-subject reduction of adaptation in TS, $F(2,38) = 45.20$, $p < .01$, and PS, $F(2,38) = 8.64$, $p < .01$, although not in VS, $F(2,38) = 0.81$, $p > .05$.

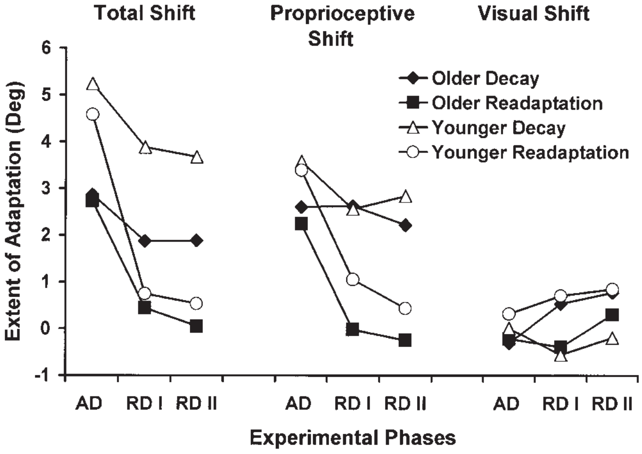

Figure 2. Extent of total shift, proprioceptive shift, and visual shift as a function of experimental phases. AD = adaptation; RD I = Reduction 1; RD II = Reduction 2.

Between-subject reduction of adaptation.—To assess the effects of age and/or the reductive treatment on the reduction of adaptation, we had to phase out the initial age-related differences in the extent of adaptation before we could perform a meaningful between-subject analysis. On the basis of this consideration, we used a multivariate analysis of covariance to examine the extent of residual adaptation (i.e., the extent of adaptation that remained after a period of decay–readaptation) during Reductions 1 and 2 with the extent of adaptation during the adaptation phase as covariates.

Results from this analysis indicated that age did not have a significant effect on the extent of residual adaptation when residual TS, PS, and VS were considered together, $F(3,33) = .10$, $p > .05$. But reductive treatment exerted a significant effect on the extent of residual adaptation, $F(3,33) = 9.27$, $p < .01$. There was no significant interaction between age and the reductive treatment, $F(3,33) = 1.31$, $p > .05$.

Because the multivariate effect of reductive treatment was significant, we used a univariate analysis of covariance (ANOCOVA) to examine residual TS, PS, and VS individually for this effect. The first ANOCOVA indicated that residual TS in the readaptation condition was significantly different from that in the decay condition, $F(1,39) = 28.09$, $p < .01$. The second ANOCOVA showed that residual PS in the readaptation condition was significantly different from that in the decay condition, $F(1,39) = 4.49$, $p < .05$. The third ANOCOVA showed that the residual VS in the readaptation condition was not statistically different from that in the decay condition, $F(1,39) = 0.04$, $p > .05$. Results from the analysis of the between-subject reduction of adaptation indicated that readaptation was more effective than decay in reducing the extent of TS and PS. The nonsignificant between-subject effect of reductive treatment in VS was expected because there was no initial reliable adaptive change in the eye-head visual system.

Analysis of Additivity

Figure 3 presents the mean extent of TS and the algebraic sum of PS and VS in each adaptation–reduction phase. In the adaptation phase, TS seemed greater than the algebraic sum of PS and VS (i.e., underadditivity). However, the situation became more complex in the two subsequent reduction phases. Among the four age–treatment subgroups, the younger decay subgroup seemed to show an underadditivity ($TS > PS + VS$), the younger readaptation subgroup and the older decay group seemed to show an overadditivity ($TS < PS + VS$), and the older readaptation subgroup seemed to show an extent of adaptation too small to warrant any serious analysis of additivity. On the basis of these observations, an overall MANOVA involving all adaptation–reduction phases was not possible. Thus, we tested each adaptation–reduction phase for additivity by a univariate analysis of variance (ANOVA). Data from the adaptation phase were submitted

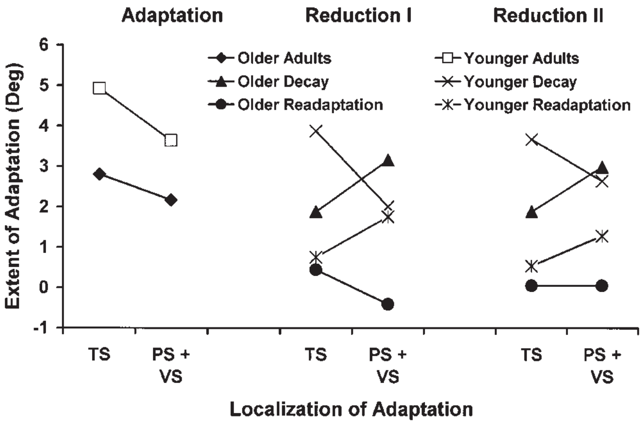

Figure 3. Extent of total shift (TS) and the algebraic sum of proprioceptive shift (PS) and visual shift (VS) during each experimental phase.

to a 2 (age: older vs. younger) × 2 (localization: TS vs. PS + VS) ANOVA. Data from the two reduction phases were individually submitted to a 2 (age: older vs. younger) × 2 (reductive treatment: decay vs readaptation) × 2 (localization: TS vs PS + VS) ANOVA.

Adaptation phase.—The first ANOVA showed that the effect of localization was not significant, $F(1,40) = 2.84$, $p > .05$, indicating that TS was not different from the algebraic sum of PS and VS. The effect of age was statistically significant, $F(1,40) = 6.37$, $p < .05$. This significant age effect was consistent with an earlier result of this study that the older participants showed a smaller extent of TS than their younger counterparts. In addition, there was no significant interaction between age and localization, $F(1,40) = 0.33$, $p > .05$.

Reduction 1.—The second ANOVA showed that the effect of localization was not significant, $F(1,38) = 0.02$, $p > .05$, indicating that TS was not different from the algebraic sum of PS and VS. The effect of age was not statistically significant, $F(1,38) = 0.93$, $p > .05$, whereas the effect of reductive treatment was significant, $F(1,38) = 5.88$, $p < .05$. In addition, there was no significant interaction between age and localization, $F(1,38) = 0.18$, $p > .05$, or between reductive treatment and localization, $F(1,38) = 0.06$, $p > .05$.

Reduction 2.—Finally, the third ANOVA showed that the effect of localization was not significant, $F(1,38) = 0.05$, $p > .05$, indicating that TS was not different from the algebraic sum of PS and VS. Again, the effect of age was not statistically significant, $F(1,38) = 0.71$, $p > .05$, whereas the effect of reductive treatment was significant, $F(1,38) = 6.16$, $p < .05$. In addition, there was no significant interaction between age and localization, $F(1,38) = 0.15$, $p > .05$, or between reductive treatment and localization, $F(1,38) = 0.03$, $p > .05$.

Taken together, these results indicated that TS equaled the algebraic sum of PS and VS, lending support to the two-component model of adaptation.

Preexposure Phase

Data on the position of the five visual targets were collected for 17 older and 12 younger participants only. Because these data were needed for us to calculate the accuracy and variability in preexposure responses, statistical analysis could not be based on all participants. Therefore, this part of the analysis included the available 29 older and younger participants only. Data on the accuracy and variability of preexposure responses were individually submitted to a two-group MANOVA (two-sample Hotelling's T^2) with eye-hand, head-hand, and eye-head systems as dependent variables.

Response accuracy.—Table 3 presents the mean response accuracy in the eye-hand, head-hand, and eye-head systems in older and younger adults. Results from the two-sample Hotelling's T^2 showed that when the eye-hand, head-hand, and eye-head systems were considered together, there was no significant difference between the two age groups, $F(3,25) = 1.27$, $p > .05$. We interpreted this finding as indicating that no age-related decrease in response accuracy occurred under undistorted visual conditions.

Response variability.—Table 4 presents the mean response variability in the eye-hand, head-hand, and eye-head systems in the older and younger adults. Results from the two-sample Hotelling's T^2 showed that when all three systems were considered together, there was no significant difference in response variability between the two age groups, $F(3,25) = 1.02$, $p > .05$. We interpreted this nonsignificant effect as indicating that no age-related increase in response variability occurred under undistorted visual conditions.

DISCUSSION

The decrease in the TS aftereffect indicates that adaptive eye-hand coordination declines with advancing age. Under the current experimental conditions, the magnitude of this decline was about 2°, or 40% of the TS aftereffect shown by the younger participants. This magnitude represents a small-to-moderate decline. Redding and Wallace (1993, 1996, 1997) have argued that the aftereffects, including the TS aftereffect, reflect contributions from spatial realignment of the sensorimotor systems. However, when participants point repeatedly at a target during prism exposure, the TS aftereffect may include a component that is added to spatial alignment from strategic control. This component is attributable to the interference of higher-level processes and may occur in the coordination of sensorimotor systems without accompanying change in individual sensorimotor systems. From

Table 3. Response Accuracy in Eye-Hand, Head-Hand Proprioceptive, and Eye-Hand Visual Tests, in Degrees, During the Preexposure Phase

	Younger ($n = 12$)		Older ($n = 17$)		
Pretest	M_1	SD_1	M_2	SD_2	Difference ($M_1 - M_2$)
Eye-hand	1.70	0.71	1.78	0.72	−0.08
Head-hand	3.28	1.69	4.52	1.65	−1.24
Eye-head	2.06	0.95	2.14	0.83	−0.08

Table 4. Response Variability in Eye-Hand, Head-Hand Proprioceptive, and Eye-Head Visual Tests, in Degrees, During the Preexposure Phase

	Younger ($n = 12$)		Older ($n = 17$)		Difference
Pretest	M_1	SD_1	M_2	SD_2	($M_1 - M_2$)
Eye-hand	1.79	1.15	1.55	0.77	0.24
Head-hand	3.01	2.12	4.03	1.62	−1.02
Eye-head	1.83	0.97	2.03	0.67	−0.20

this perspective, age-related changes in the TS aftereffect may be interpreted as indicating that strategic control processes are less available in older adults. That strategic control changes with age is reflected by the fact that the significant decrease in the TS aftereffect was twice as great as the nonsignificant decrease in the PS aftereffect.

Age-related decrease in strategic control was corroborated by the analysis of additivity. As indicated earlier, the significant age-related decrease was limited to the TS aftereffect. The failure to find any age-related decrease either in the PS aftereffect or in the algebraic sum of PS and VS aftereffects indicates evidence of underadditivity. Although the TS aftereffect was not statistically different from the algebraic sum of PS and VS aftereffects during each adaptation–reduction phase, the possibility of a third component in the TS aftereffect cannot be entirely ruled out. This component might not be large enough to statistically distinguish the TS aftereffect from the algebraic sum of PS and VS aftereffects, presumably because the between-subject variability in the PS and VS aftereffects was large. But this component was certainly large enough to statistically distinguish the two age groups in the TS aftereffect whose between-subject variability was smaller. We interpreted such underadditivity as indicating that younger adults were better able to deploy adaptive coordination processes to improve exposure performance, and the similarity between prism exposure and the eye-hand coordination test (e.g., head fixed facing straight ahead) produced transfer of adaptive coordination to the TS aftereffect.

It is tempting to conclude that the age-related decrease in perceptual-motor adaptability is entirely attributable to the strategic control processes that are less available in older adults. However, such a conclusion seems to be unwarranted. As shown in Table 1, the younger participants exceeded their older counterparts in the PS aftereffect by 1.06°. Although not statistically significant, this difference was likely to have contributed to the age-related decrease in the TS aftereffect. On the basis of this consideration, we suggest that the age-related decline in the TS aftereffect is attributable to change in strategic control and, to some degree, decrease in spatial alignment.

It is not surprising that the VS aftereffect did not appear in the present experiment, because visual feedback was available early in the pointing movement (concurrent exposure) during prism exposure. Previous studies indicated that adaptation under early visual feedback condition led to little or no change in the eye-head visual system (Cohen, 1967; Redding & Wallace, 1988a, 1988b, 1992, 1994; Uhlarik & Canon, 1971). As described previously, the perceptual-motor system can be conceptualized as a strategic linkage of sensorimotor systems (Redding & Wallace, 1988a, 1996, 1997). Within such a linkage, one system guides and the other is guided. When misalignment is detected, the guided system is realigned to agree with the guiding system. Thus, realignment occurs in the guided system. The direction of guidance can be influenced by the availability of visual feedback in a pointing movement. Under the early visual feedback condition, the eye-head visual system guides the head-hand proprioceptive system. As a result, realignment appears in the head-hand proprioceptive system, but not in the eye-head visual system. Neither age group showed any noticeable VS, indicating that the principle established in these earlier studies applies to different adult populations.

It seems counterintuitive that a significant decrease in the extent of adaptation was not accompanied by a corresponding increase in response variability of adaptation. However, there has been evidence that the two aspects of prism adaptation are not necessarily related. Bossom (1965) reported that prism adaptation in animals with brain lesions showed no increase in response variability despite a significant decrease in the extent of adaptation. Bossom concluded that the effect of a lesion was restricted to perceptual-motor adaptability and did not disrupt normal perceptual-motor function. On the basis of our present results, we tentatively suggest that aging affects perceptual-motor function in a similar way. Namely, aging of the nervous system selectively affects perceptual-motor adaptability and spares normal perceptual-motor coordination.

Reduction in the TS aftereffect showed two distinctive patterns. Over a period of 10 min, readaptation led to a significantly reduced extent of adaptation, whereas decay led to little or no reduction. These findings were consistent with an earlier report that, over a 10-min postexposure period, rapid reduction of adaptation occurred in the readaptation condition, whereas little or none occurred in the decay condition (Welch, Bleam, & Needham, unpublished 1970 study, cited in Welch, 1978). However, Hamilton and Bossom (1964) found that both decay and readaptation significantly reduced the extent of adaptation over a period of 15 min, and readaptation was not more effective than decay in such reduction. Given the small number of studies available, it seems imprudent to draw a conclusion at this time. More research is clearly needed.

Despite its influence on the adaptation process, age did not seem to exert an equal influence on the reduction process. The failure to find a significant effect of age on the residual TS aftereffect in the decay condition may help explain the etiology of decline in adaptive eye-hand coordination. Two candidates were identified earlier in this report: (a) biological changes of the perceptual-motor system and (b) interference of past perceptual-motor habits. On a theoretical basis, given that the extent of initial TS aftereffect was smaller in older adults, a slower return of normal eye-hand coordination in the same age group would support the biological explanation, whereas a faster return of normal eye-hand coordination would support the interference explanation. Because the two age groups showed no difference in the rate of return of normal coordination, neither explanation could account for the etiology of decline alone. Instead, it is reasonable to assume that both biological changes of the perceptual-motor system and the interference of past perceptual-motor habits play a role in this decline.

Preexposure responses showed no age-related decline in accuracy or variability. Because vision was undistorted during this phase of the experiment, these results indicate that normal perceptual-motor function, as reflected by response accuracy and variability, does not decline with advancing age. However, Chaput and Proteau (1996) reported that older participants showed larger root mean squared errors in pointing movements than their younger counterparts. The discrepancy between these two studies may be explained by different speeds of hand movement: 400–500 ms in the Chaput and Prodeau study and 2,000 ms (for the "out" part of the hand movement only) in the present study. A more stringent constraint on the speed of hand movement may disrupt normal perceptual-motor functions more severely in older adults than in younger adults.

Our results show that perceptual-motor adaptability declines with advancing age. This decline may be due to age-related change in strategic control and, to some extent, decrease in spatial alignment. We were not able to make a conclusion regarding the localization of the possible decrease in spatial alignment because the exposure condition (i.e., early visual feedback) did not support development of realignment in the eye-head visual system. Both biological changes of the perceptual-motor system and interference of past perceptual-motor habits may have contributed to such a decline. Finally, we also found that aging selectively affects perceptual-motor adaptability and spares normal perceptual-motor coordination.

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Address correspondence to Jinhua Guan, Division of Safety Research, National Institute for Occupational Safety and Health, 1095 Willowdale Road, MS P119, Morgantown, WV 26505-2888. E-mail: jguan@cde.gov

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