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Reorganization of Prehension Components Following Perturbation of Object Size

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This study provides a kinematic comparison of the response of 12 older persons (ages 60–70) and 12 young persons (ages 20–26) to a perturbation of object size during a reach-to-grasp movement. For 80 out of 100 trials, each participant reached to grasp an illuminated cylinder of either small or large diameter (0.7 and 8.0 cm, respectively). For 20 out of 100 trials, a visual perturbation occurred at movement onset. This perturbation consisted of a switch of illumination from 1 to the other cylinder. For the switch from large to small cylinder, participants changed the distal grasp from whole-hand prehension to precision grip. For the opposite switch, participants changed from precision grip to whole-hand prehension. The older participants successfully adapted to these perturbations but showed a more conservative approach. Generally the approach time as the hand neared the object was prolonged, and the coordination between transport and manipulation components was maintained when comparing perturbed with nonperturbed trials. Young participants showed a more flexible pattern with a decrease or loss of temporal coupling between the components. It is hypothesized that the more rigid movement pattern of older participants to unanticipated motor requirements could be a contributory factor to the higher incidence of accidents for this group.

Recent studies have used the perturbation paradigm to elucidate the sensorimotor neural processes of human movement. In such paradigms, the participant is unexpectedly presented with the requirement to change motor task. For example, an initially presented stimulus can suddenly be replaced by an alternative stimulus, and the participant must adapt motor output accordingly. Such a visual perturbation can be presented at different stages of the premovement and movement periods. With kinematic studies of the reach-to-grasp movement, visual perturbation is often given at movement onset. Thus, just as the participant begins to reach for an object at a particular location, an object at a different location is displayed. The participant must then quickly change the length (Gentilucci, Chieffi, Scarpa, & Castiello, 1992; Scarpa & Castiello, 1994) or direction (Castiello, Paulignan, & Jeannerod, 1991; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991) of the reaching movement to grasp this latter object. Object size can also be perturbed. For example, the participant can begin a reaching movement for a small target but then have to quickly change for the grasp of a larger object (Castiello, Bennett, & Paulignan, 1992; Castiello, Bennett, & Stelmach, 1993; Castiello & Jeannerod, 1991; Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991). This requires a change from the initially planned precision grip to a grasp such as whole-hand prehension (Castiello et al., 1992, 1993).

The aim of such double-step perturbation paradigms is to determine the central nervous system response to an unexpected motor requirement. In the temporal domain, such experiments can assist in determining how quickly the system adapts to the perturbation. How soon is the initial output suppressed and the second output initiated? With regards to quality of movement, kinematic analyses show how the movement has been reorganized. Thus, previous studies of young participants (ages 18–35) demonstrated a rapid and smooth change from one to another grasp type when object size was perturbed at movement onset (Castiello et al., 1991, 1992, 1993).

The ability of older participants to respond to a visual perturbation has been little investigated. With nonperturbed movements, older participants generally show longer reaction times and movement durations than younger participants (Stelmach & Goggin, 1989; Stelmach & Nahom, 1992; Welford, 1977, 1984). From such results, one could tentatively suppose that this generalized slowness would also be evident when older participants must unexpectedly change motor output. Stelmach, Goggin, and Amrhein (1988) used a precue paradigm to assess the time taken to restructure a planned motor response. For most trials (75%), the premovement cue corresponded to the subsequent extent, direction, and limb used in the aiming task. However, for some trials (20%), the cue was invalid; this obliged the participant to unexpectedly restructure one or more movement parameters. Both older and younger participants showed an increase of reaction time for these latter invalid precue trials. However, the reaction time for the older participants was greater. This suggested that the older participants needed more time to restructure a planned motor response.

The current study gives a kinematic assessment of the ability of older participants to respond to a visual perturbation. At the

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onset of a reaching movement, the size of the object to be grasped is unexpectedly changed. In other words, the participant plans to grasp an object of a particular size, but on movement initiation must quickly change motor output to grasp an object of a different size.

The aim of this study is to compare the kinematic patterning of the perturbed movement of older participants with that of younger participants. In a previous study of a nonperturbed reaching-to-grasp movement, Bennett and Castiello (1994) demonstrated that older participants are slower and more cautious. The stage at which the arm decelerates toward the object is also longer for this group than for the younger group. Despite such generalized slowness, the kinematic patterning of the movement is appropriate. For example, the temporal coordination between the transport (reach) and manipulation (grasp) components is maintained. Similarly, the grasp for the smaller object differs from that for the larger object. Such results confirm the view of Salthouse (1985) that older participants show a conservation of motor patterning, but that they also show a general slowness. In the current study, we predicted that the older participants would show appropriate responses to visual size perturbation but that the perturbed movement would be executed more slowly.

Method

Participants

The older group consisted of 6 women and 6 men between 60 and 70 years old (M = 66 years, SD = 3.8). These participants were either employed by the University of Padova or by the European Medical Center and were selected randomly from a large group of volunteers. The young participant group consisted of 12 gender-matched undergraduate students ranging in ages from 20 to 26 years (M = 23 years, SD = 2.8). These participants were also randomly selected from a volunteer group. Exclusion criteria that were applied to both participant groups included the following: history of neurological disorders, skeletomotor disorders (such as arthritis), use of medication (particularly psychoactive drugs), psychiatric illness, and visual defects. Visual acuity was 20/30 or better for both groups (younger participants: M = 22/23; older participants: M = 22/27). All participants were native Italian speakers and lived independently. Participants showed right-handed dominance according to the Edinburgh inventory (for both groups, M = 19/19; Oldfield, 1971). The mean number of formal education years was 15 (SD = 3.0) and 12 (SD = 4.2) for the younger and older participant groups, respectively. This difference was not significant. The younger participants outperformed older participants on the Digit Symbol Substitution (DSS) subtest of the Wechsler Adult Intelligence Scale—Revised (WAIS-R; Wechsler, 1981). Mean DSS scores for the young and older participants were 67.7 (SD = 10.8) and 52.3 (SD = 7.2), respectively; $t(20) = 7.2$, $p < .01$. Older participants performed better on the Vocabulary subscale of the WAIS-R. The mean score for older participants was 61.2 (SD = 3.8) and that for younger participants was 56.7 (SD = 5.5), $t(20) = 6.3$, $p < .01$. All participants were unaware of the experimental design or purpose.

Materials

The experiment was conducted in a dimly lit room. The working surface was a rectangular table. The participant was seated on a height-adjustable chair so that the thorax pressed gently against the front edge of the table and the feet were supported. A pressure-sensitive starting switch was positioned 10 cm anterior to the participant's midline. With the ulnar side of the hand placed on this switch, the starting position was as follows: slight shoulder flexion, 90° elbow flexion, semipronation of the forearm, 5–10° wrist extension, and opposition between the pads of the index finger and thumb. Reflective passive markers (0.5 cm diameter) were secured to the following points of the reaching limb: (a) wrist—radial aspect of the distal styloid process of the radius; (b) dorsal aspect of the first carpo-metacarpal joint; (c) thumb—ulnar side of the nail; and (d) index, middle, and fourth fingers—radial side of the nail. Movements were recorded with the Elite system (Ferrigno & Pedotti, 1985). This consisted of two infrared cameras (sampling rate 100 Hz) inclined at an angle of 30° to the vertical and placed 3 m in front of the table and 3 m apart. The calibrated working space was a parallelepiped (length = 60 cm, width = 30 cm, and height = 60 cm) from which the spatial error measured from stationary and moving stimuli was 0.4 mm. Calibration was performed with a grid of 25 markers (5 × 5). The centroid of each marker was placed 15 cm from that of another. Using the procedure of Haggard and Wing (1990), the mean length of a bar with two markers attached, as reconstructed from the Elite data, was 14.93 cm (SD = 0.22). Coordinates of the markers were reconstructed with an accuracy of 1/3,000 over the field of view and sent to a host computer (IBM 386). The standard deviation of the reconstruction error was 1/3,000 for the vertical (y) axis and 1.4/3,000 for the two horizontal (x and z) axes.

The target stimuli to be grasped were two translucent Perspex cylinders (see Figure 1). A small cylinder (diameter = 0.7 cm, height = 10 cm, and weight = 9 g) stood vertically within the center of a large cylinder (diameter = 7.5 cm, height = 8 cm, and weight = 202 g). The small cylinder was thus slightly higher than the large cylinder. Prior to each trial, both cylinders were visible but not illuminated. They were positioned over three computer-controlled light emitting diodes (LEDs) implanted in the table surface 35 cm anterior to the starting switch in the midline. With activation of the central LED, only the small cylinder was illuminated. With activation of the two lateral LEDs, only the large cylinder was illuminated. Perturbation of object size was achieved by a shift of illumination (Castiello et al., 1991, 1992, 1993; Paulignan, Jeannerod, et al., 1991). This was triggered immediately on release of the starting switch, that is, at the onset of the reaching (transport) movement. For a perturbation from the large to the small cylinder, the initially activated lateral LEDs were deactivated, and the central LED was activated. The participant thus initially saw the large cylinder illuminated but, on initiation of the reach movement, saw a shift of illumination to the small cylinder and was required to grasp the latter target. For a perturbation from the small to the large cylinder, the initially activated central LED was deactivated, and the two lateral LEDs were activated. The participant thus initially saw the small cylinder but, on movement initiation, saw a shift of illumination to the large cylinder and was required to grasp the latter target.

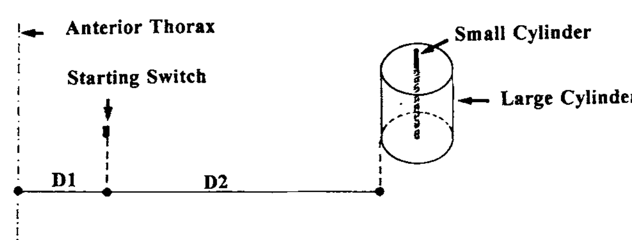

Figure 1. Schematic representation of the experimental setup. D1 = distance between anterior thorax and starting switch (10 cm); D2 = distance between starting switch and target cylinders. In this example, the central small diameter cylinder is illuminated.

Procedure

The participant was instructed to begin the movement as soon as a cylinder became illuminated, and then reach for, grasp, and lift the cylinder. No instructions were given as to speed of initiation, speed of movement, or accuracy. This was to ensure that the participants performed the movement as naturally as possible within the constraints of the experimental paradigm. For 10 practice trials, all participants adopted a precision grip (PG, opposition between the index finger and thumb; Napier, 1956) to grasp the small cylinder and adopted a whole-hand prehension (WHP, all fingers opposing the thumb) to grasp the large cylinder. Prior to each trial, a tone (880 Hz, duration of 250 ms) was generated. To reduce expectancy and rhythmical effects, the duration between this tone and illumination was randomly set at 500, 1,000, 1,500, or 2,000 ms. During each trial, the experimenter ascertained continued on-line detection of the markers, and, if any markers were not visible, the trial was rejected. Computer control of a further trial was then initiated, and 2 s later a tone for this new trial sounded. Data acquisition began with illumination of the cylinder and continued until after the cylinder had been lifted. Experimentation continued until the required number of successful trials was collected.

The majority of the 100 trials were nonperturbed; that is, either the small (n = 40) or the large (n = 40) cylinder was illuminated, and this same cylinder remained illuminated until after completion of the trial. For 20% of the trials, a visual perturbation occurred immediately on movement onset (see *Materials* section). These perturbed trials were random and interspersed with the nonperturbed trials. The perturbation consisted of a shift of illumination either from the large to the small cylinder (n = 10) or from the small to the large cylinder (n = 10). These perturbations thus promoted the shift from one grasp pattern to another, that is, from WHP to PG, or vice versa.

Data Processing and Analysis

The Elite processing package was used to assess the data. This package gave a three-dimensional reconstruction of the marker positions. The data were then filtered by means of a FIR linear filter and a transition band of 1 Hz (sharpening factor = 2; D'Amico & Ferrigno, 1990, 1992). Analysis of the transport component was based on kinematics of the wrist marker: trajectory, velocity, and acceleration. Onset of this component was taken as the time shortly after illumination and release of the starting switch, at which the wrist marker exceeded a displacement of 0.4 mm. (Note that the calibration procedure found a spatial error of 0.4 mm. By progressively scanning each frame of the wrist marker trajectory profile, a difference between two successive frames that is less than 0.4 mm indicates that the marker is not moving; any difference greater than 0.4 mm indicates movement.) Movement completion was taken as the time of object grasp at which the distance between the thumb and index finger markers was constant, indicating that the cylinder had been grasped as well as the end of both the transport and manipulation components. The lifting feature of the task was not assessed. Movement duration refers to the time between onset and completion. Temporal measures included the times taken to reach peak velocity, peak acceleration, and peak deceleration and the time from peak velocity to the end of the transport component (deceleration time); each value was expressed in both absolute and relative terms (i.e., as a percentage of movement time). The amplitudes of peak velocity, peak acceleration, and peak deceleration were also determined.

Analysis of the manipulation component was based on the kinematics of the hand and digit markers: trajectory of each digit, grip aperture, and the rate of change of the grip aperture. Temporal measures, again expressed in both absolute and relative terms, included the time to peak aperture and, in cases of a second aperture (see Results section), the onset time of this second opening (calculated with a break detection algorithm that uses the trapezoidal rule to give a sliding calculation of the integral of an array relative to a baseline value; see Appendix of Castiello et al., 1993, for more details) and the time of its peak. Middle and fourth finger trajectories were also analyzed. The time at which the index finger deviated from the more ulnar digits for specification of PG could thus be determined (Castiello et al., 1993). Amplitude measures included the amplitude of the first, and when present, second peak of aperture between the index finger and thumb.

For each participant, mean values of each dependent measure were calculated for each Group (old vs. young) × Type of Trial (nonperturbed vs. perturbed) interaction. These data were entered into two multivariate analyses of variance (MANOVAs) where group was the between-subjects variable and type of trial was the within-subject variable. For one MANOVA, data obtained from PG nonperturbed trials were compared with PG → WHP perturbed trials. This comparison enabled an assessment of the way in which the PG motor output was halted and the WHP pattern was executed. As such, early changes to the temporal patterning of the initial movement in response to the perturbation can be determined. For the other MANOVA, data from WHP nonperturbed trials were compared with WHP → PG trials. Thus the comparison was between a WHP movement that was completed and a WHP movement that was interrupted. An alpha level of .05 was adopted for all tests of significance, and the magnitude of the effects was confirmed by determining the proportion of the total variance associated with each variable. Post hoc contrasts were with the Newman–Keuls testing procedure. For each type of trial and for each participant, the correlation coefficient between the peak of arm deceleration (transport component) and the peak of grip aperture (manipulation component) was determined by linear regression analysis. The Fisher's Z transformation of data was used for homogeneity of variance and to counteract any nonnormal distributions. The significant difference of each r value from zero was determined with analyses of variance (ANOVAs). For the comparison of correlation coefficients, data pairs were combined (n = 120 for each type of trial and for each participant group), linear regression analysis was performed, and differences among correlations were tested using z scores.

Results

Overall, the older participants showed no obvious difficulty in responding to the perturbation. They suitably and rapidly switched from one grasp type to the other for perturbed trials. For the perturbation from the large to the small cylinder, they changed the initial WHP grasp to a PG between the index finger and thumb. For the perturbation from the small to the large cylinder, they changed the initial PG to a WHP, that is, to a grasp involving all the digits. They showed no examples of errors such as grasping the wrong cylinder, accidentally knocking over the cylinders, or dysmetric reaches (under- or overshooting).

Movement Initiation Time

Movement initiation time refers to the time between illumination of the target cylinder and onset of the reaching movement; the results are shown in Table 1. Although mean movement initiation time was lower for older than for younger participants, this difference was not statistically significant. There was no effect for group: WHP → PG/WHP, $F(1, 22) = 1.68$, $p = .21$; PG → WHP/PG, $F(1, 22) = 1.48$, $p = .24$. Of importance is that the mean value for perturbed trials of both participant groups did not differ from that for nonperturbed trials. There was no effect for type of trial: WHP → PG/WHP, $F($1,

Table 1
Results for Movement Initiation Time and Movement Duration (in Milliseconds)

Response variable	Older participants: Perturbed	Older participants: Nonperturbed	Younger participants: Perturbed	Younger participants: Nonperturbed
Initiation time				
WHP → PG/WHP	380 (110)	375 (116)	442 (53)	433 (51)
PG → WHP/PG	378 (133)	379 (132)	430 (66)	435 (58)
Movement duration				
WHP → PG/WHP	1,050 (151)	990 (180)	830 (110)	834 (100)
PG → WHP/PG	1,152 (194)	1,103 (195)	905 (120)	888 (116)

Note. Numbers in parentheses are standard deviations. WHP → PG/WHP = perturbed trials from whole-hand prehension to precision grip and nonperturbed, whole-hand prehension trials; PG → WHP/PG = perturbed trials from precision grip to whole-hand prehension and nonperturbed, precision grip trials.

22) = 2.08, $p = .16$; PG → WHP/PG, $F(1, 22) = .36$, $p = .56$. This indicated that there were no expectancy effects; that is, neither participant group predicted when a perturbed trial would be presented.

Movement Duration

In general, movement duration was greater for older than for younger participants. There was the following group effect: WHP → PG/WHP, $F(1, 22) = 9.32$, $p < .01$; PG → WHP/PG, $F(1, 22) = 9.63$, $p < .01$. A further difference was that the older participants showed a longer movement duration for perturbed than for nonperturbed trials (see Table 1). This was not always the case for the younger participants. The mean movement duration for perturbed WHP → PG trials (1,050 ms) of older participants was greater than that for nonperturbed WHP trials (990 ms, $p < .05$), Group × Type of Trial interaction, $F(1, 22) = 4.67$, $p < .05$. Younger participants did not show such a difference. For the opposite perturbation (PG → WHP), mean movement duration for older participants (1,152 ms) was again greater than for nonperturbed PG trials (1,103 ms, $p < .05$), Group × Type of Trial interaction, $F(1, 22) = 9.04$, $p < .01$. The younger participants who performed the perturbed movement with a double-grip pattern (as discussed later) also showed a longer movement duration for perturbed (883 ms) than for nonperturbed trials (832 ms, $p < .05$), Young Group × Type of Trial interaction, $F(1, 10) = 7.03$, $p < .05$. Those younger participants who used a single-grip pattern did not show a greater movement duration for perturbed trials.

Transport Component

The transport component is the reaching part of the movement. Table 2 shows the results for the key kinematic parameters, which were measured from the velocity and acceleration profiles of the wrist marker.

The parameter of deceleration time showed clear differences between the two groups (see Table 2). This parameter indicates the time taken by the arm to decelerate as it hones in on the target cylinder, that is, the final part of the movement. Irrespective of whether there was a perturbation, deceleration time was longer for the older participants. The following group effects were found: WHP → PG/WHP, absolute $F(1, 22) = 21.13$, $p < .0001$; relative $F(1, 22) = 16.17$, $p < .001$; and PG → WHP/PG, absolute $F(1, 22) = 18.44$, $p < .0001$; relative, $F(1, 22) = 32.09$, $p < .0001$. As an example, for the nonperturbed PG trials, the mean deceleration time of the older participants was 715 ms (64% of movement duration), a value well above the mean of 474 ms (54%) for the younger participants.

Not only did the older participants show a generally longer deceleration time, but they also showed a different patterning of this parameter in response to perturbation (see Table 2). For only the older group, deceleration time was longer for perturbed than for nonperturbed trials. This is demonstrated in Figures 2 and 3. By looking at the velocity and acceleration profiles, it can be seen that the period between peak velocity (zero crossing of the acceleration curve) and the end of the movement is longer for the perturbed (dotted line) than for the nonperturbed trials of these 2 older participants. In contrast, there is no difference of deceleration time between perturbed and nonperturbed trials of the younger participants. There were significant interactions between the group variable and type of trial variable when comparing the two groups across the WHP → PG/WHP conditions, absolute $F(1, 22) = 5.45$, $p < .05$; relative $F(1, 22) = 5.03$, $p < .05$. Posthoc comparisons revealed that mean deceleration time for the perturbed WHP → PG trials of the older participants (661 ms, 62%) was greater than that for the nonperturbed WHP trials (594 ms, 60%; $ps < .05$). No such difference was found for the younger participants (435 ms, 53%, and 442 ms, 52%, respectively). There were also significant Group × Type of Trial interactions when comparing the two groups across the PG → WHP/PG conditions, absolute $F(1, 22) = 8.02$, $p < .01$; relative $F(1, 22) = 4.12$, $p < .05$. Again, post hoc testing showed that the deceleration time for perturbed PG → WHP trials of the older participants (764 ms, 66%) was longer than that for nonperturbed PG trials (715 ms, 64%; $ps < .05$). The younger participants did not show this significant extension to deceleration time with perturbation (488 ms, 54%, and 474 ms, 54%, respectively).

The amplitudes of the acceleration and velocity peaks also showed perturbation responses that were different for the older participants (see Table 2). For the WHP → PG/WHP conditions, significant Group × Type of Trial interactions were found for the amplitudes of both the acceleration, $F(1, 22) = 9.33$, $p < .01$, and the velocity peaks, $F(1, 22) = 4.27$, $p < .05$. Post hoc comparisons confirmed that only the older participants showed a lower amplitude

Table 2
Results for the Transport Component

Response variable	Older participants: Perturbed	Older participants: Nonperturbed	Younger participants: Perturbed	Younger participants: Nonperturbed
		WHP → PG/WHP		
Deceleration time	661 (118)	594 (123)	435 (59)	442 (58)
Relative value (%)	62 (5)	60 (7)	53 (5)	52 (4)
Peak acceleration: Time	280 (63)	310 (98)	238 (50)	249 (58)
Relative value (%)	27 (3)	31 (4)	28 (4)	30 (3)
Amplitude (mm/s²)	2,723 (720)	3,452 (980)	4,200 (2,064)	4,400 (2,361)
Peak velocity: Time	389 (62)	396 (61)	395 (80)	392 (80)
Relative value (%)	38 (3)	38 (4)	47 (4)	48 (5)
Amplitude (mm/s)	532 (76)	600 (88)	620 (86)	652 (84)
Peak deceleration: Time	606 (85)	624 (82)	510 (86)	568 (85)
Relative value (%)	58 (6)	64 (8)	62 (8)	69 (5)
Amplitude (mm/s²)	2,638 (812)	2,603 (638)	3,400 (624)	3,341 (699)
		PG → WHP/PG		
Deceleration time	764 (210)	715 (163)	488 (81)	474 (54)
Relative value (%)	66 (5)	64 (6)	54 (5)	54 (4)
Peak acceleration: Time	290 (57)	286 (69)	231 (45)	273 (58)
Relative value (%)	25 (3)	26 (3)	25 (3)	30 (3)
Amplitude (mm/s²)	2,701 (893)	2,753 (863)	3,002 (716)	3,298 (840)
Peak velocity: Time	388 (64)	388 (52)	418 (68)	416 (78)
Relative value (%)	34 (4)	36 (4)	46 (5)	46 (4)
Amplitude (mm/s)	621 (85)	560 (73)	542 (53)	592 (60)
Peak deceleration: Time	598 (85)	650 (87)	518 (71)	622 (87)
Relative value (%)	52 (5)	59 (6)	57 (4)	70 (6)
Amplitude (mm/s²)	2,701 (832)	2,412 (800)	2,557 (817)	2,685 (565)

Note. Values are in milliseconds unless otherwise indicated. Each value is the interparticipant mean. The standard deviation is shown in parentheses. For temporal values, the percentage relative value (expressing the absolute value as a percentage of movement duration) is shown below the absolute value in ms.

of peak acceleration and peak velocity for perturbed WHP → PG (2,723 mm/s^2 and 532 mm/s, respectively) than for nonperturbed WHP trials (3,452 mm/s^2 and 600 mm/s, respectively; $ps < .05$). An example is shown in Figure 2. Such significant differences were not found for the younger participants (4,200 mm/s^2 and 620 mm/s and 4,400 mm/s^2 and 652 mm/s, respectively). For the PG → WHP/PG conditions, a significant Group × Type of Trial interaction was found for the amplitude of the velocity peak, $F(1, 22) = 12.75$, $p < .01$. Post hoc testing showed that the older participants showed a greater amplitude of peak velocity for perturbed (621 mm/s) than for nonperturbed trials (560 mm/s; $p < .05$). Conversely, the amplitude of peak velocity for the younger participants was less for the perturbed PG → WHP (542 mm/s) than for nonperturbed PG trials (592 mm/s; $p < .05$). Examples of these different perturbation responses are shown in Figure 3.

Despite these differences between the two groups, there was also evidence that the response to perturbation by the older participants was similar to that by the younger participants. Of note is that both groups showed modifications to the temporal organization of the transport component even though the perturbation was directed most obviously at the manipulation component. The type of trial variable was significant for the temporal settings of the peaks of acceleration and of deceleration when comparing the perturbed WHP → PG with the nonperturbed WHP trials: acceleration—absolute $F(1, 22) = 4.72$, $p < .05$; relative, $F(1, 22) = 6.88$, $p < .05$; deceleration—absolute $F(1, 22) = 17.18$, $p < .0001$; relative $F(1, 22) = 25.68$, $p < .001$. Thus, peak acceleration for the perturbed WHP → PG trials of the older participants was at 280 ms (27%) but for nonperturbed WHP trials was at 310 ms (31%). Peak deceleration of the perturbed older group trials occurred at 606 ms (58%) but for nonperturbed trials occurred at 624 ms (64%). Such anticipation in the perturbed trials was also shown by the younger participants (see Table 2). The type of trial variable was also significant for the temporal setting of the peak of deceleration when comparing the perturbed PG → WHP with the nonperturbed PG trials, absolute $F(1, 22) = 25.73$, $p < .0001$; relative $F(1, 22) = 36.12$, $p < .0001$. For the older participants, peak deceleration occurred at 598 ms (52%) for perturbed PG → WHP trials but occurred at an average of 650 ms (59%) for nonperturbed PG trials. A similar anticipation of this peak was found for the younger participants (518 ms, 57%, and 622 ms, 70%, respectively).

Manipulation Component

The manipulation component refers to the action of opening and then closing the hand on the cylinder. Results for the kine-

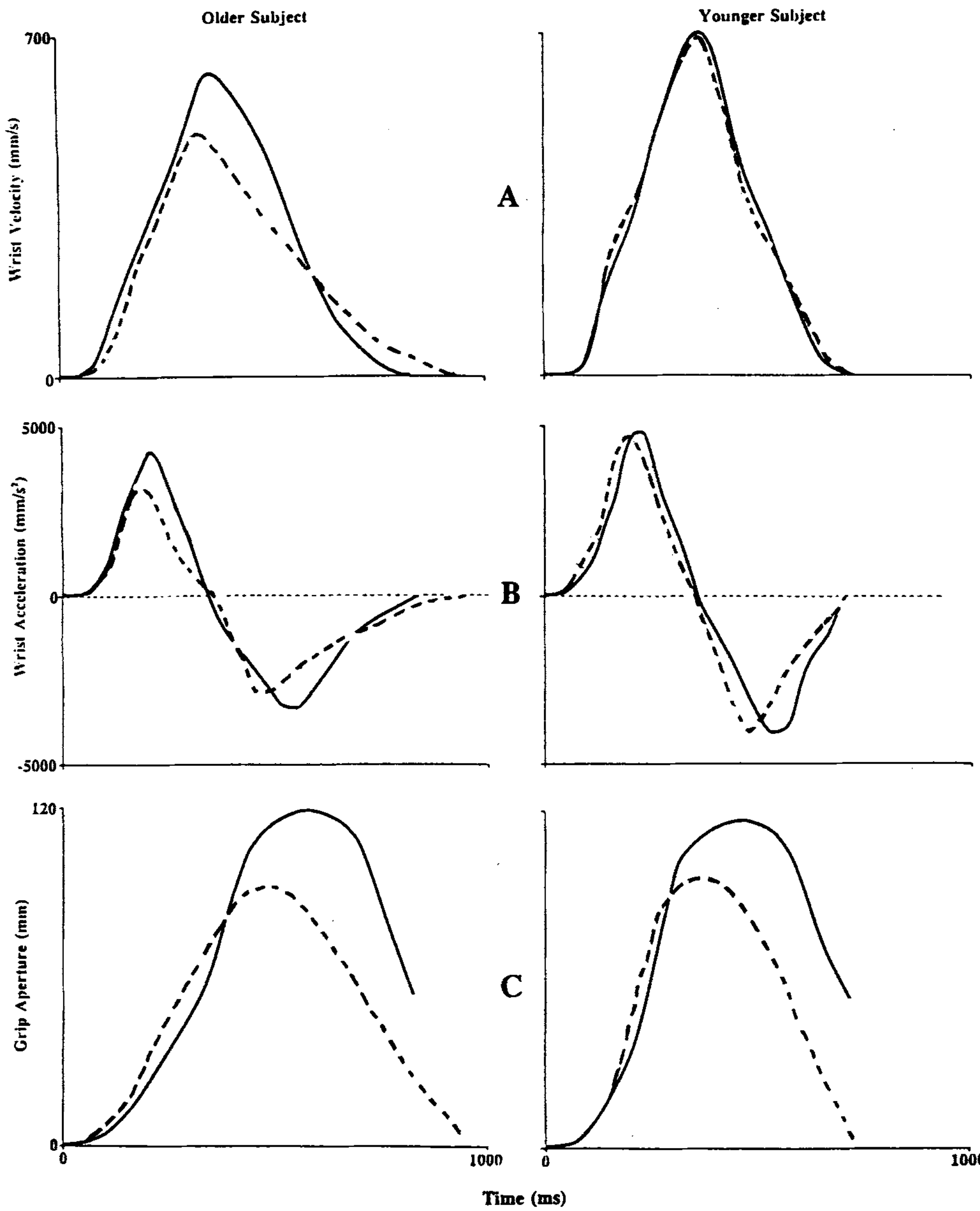

Figure 2. Perturbation from whole-hand prehension to precision grip for an older participant (C. E.) and for a younger participant (S. M.). For each trace, the solid line shows a single nonperturbed trial and the dashed line shows a single perturbed trial. A = velocity profile; B = acceleration profile; C = grip aperture profile.

matic parameters are shown in Table 3. Figure 2 (bottom row) gives representative examples of the grip aperture profiles for the perturbed WHP → PG (dotted line) and the nonperturbed WHP trials. It can be seen that both groups show a similar pattern. Most obviously, the amplitude of the peak of grip aperture is lower for perturbed than for nonperturbed trials: type of trial variable, $F(1, 22) = 188.2$, $p < .0001$. For the old and young participants, peak grip aperture was 74 mm and 72 mm, respectively, for the perturbed WHP → PG trials but was 124 mm and 123 mm, respectively, for the nonperturbed WHP trials. The similarity of these means and the lack of group effects demonstrates that the older participants did not over- or underscale hand aperture in response to the perturbation. Both groups also showed a similar pattern in response to the opposite perturbation; examples are shown in Figure 3 (bottom row). In this case, peak grip amplitude can be seen to be greater for perturbed PG → WHP trials than for nonperturbed PG trials: type of trial variable, $F(1, 22) = 56.51$, $p < .0001$. For the old and young participants, the mean peak grip apertures for perturbed PG → WHP trials were 122 mm and 94 mm, respectively, whereas for nonperturbed PG trials, the means were 62 mm and 54 mm, respectively. The significant group effect, $F(1, 22)$

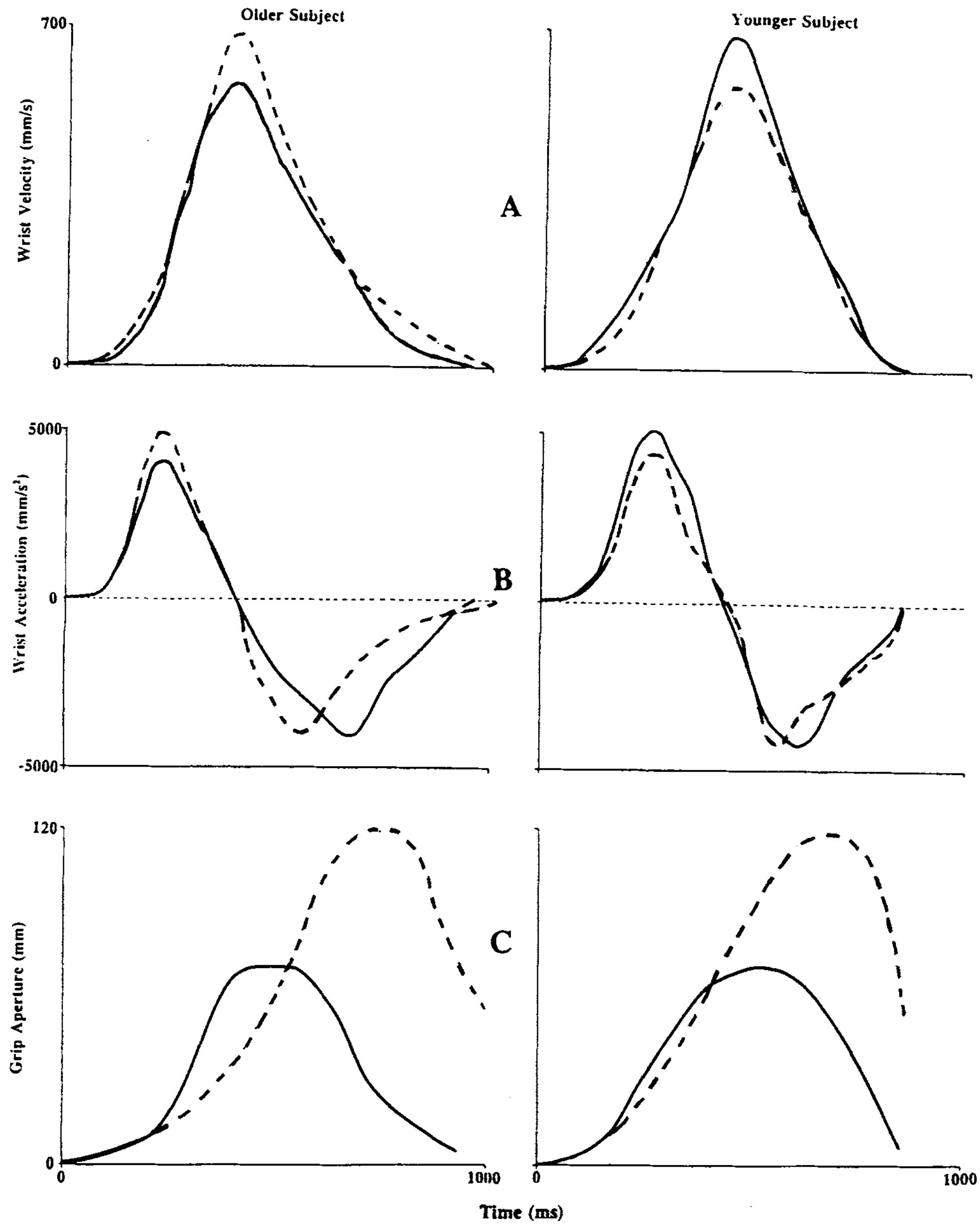

Figure 3. Perturbation from precision grip to whole-hand prehension for an older participant (P. S.) and for a younger participant (J. M.). For each trace, the solid line shows a single nonperturbed trial and the dashed line shows a single perturbed trial. A = velocity profile; B = acceleration profile; C = grip aperture profile.

= 10.36, $p < .01$, demonstrated that the older participants generally overscaled the grip aperture.

In general, with perturbed and nonperturbed trials collapsed, temporal settings of the key manipulation component parameters were later for the older than for the younger participants. Specification for PG refers to the time at which the trajectory of the index finger begins to be independent of the trajectories of the more ulnar fingers. As shown in Table 3, this value was clearly greater for the perturbed WHP → PG trials of the older participants (480 ms, 47%) than for those of the younger participants (270 ms, 34%). There was the following group effect: absolute $F(1, 10) = 20.6, p < .0001$; relative $F(1, 10) = 23.5, p < .0001$. A group effect was also found for this parameter when assessing the PG → WHP/PG conditions: absolute $F(1, 22) = 8.03, p < .05$. Specification for both the perturbed and nonperturbed trials of the older participants (M = 240 ms) was later than that of the younger participants (M = 190 ms). The time of peak grip aperture was also generally later for the older group. There were the following group effects: WHP → PG/WHP, $F(1, 22) = 4.65, p < .05$; PG → WHP/PG, $F(1, 22) = 18.65, p < .0001$. Irrespective of whether the trial was per-

Table 3
Results for the Manipulation Component

Response variable	Older participants: Perturbed	Older participants: Nonperturbed	Younger participants: Perturbed	Younger participants: Nonperturbed
	WHP → PG/WHP			
Specification for precision grip:				
Time (ms)	480 (110)		270 (58)	
Relative value (%)	47 (6)		34 (7)	
Peak grip aperture: Time (ms)	562 (117)	650 (155)	459 (76)	544 (83)
Relative value (%)	53 (5)	66 (7)	55 (5)	66 (7)
Amplitude (mm)	74 (15)	124 (8)	72 (5)	123 (12)
	PG → WHP/PG			
Specification for precision grip:				
Time (ms)	232 (31)	248 (52)	170 (28)	210 (43)
Relative value (%)	20 (3)	24 (5)	20 (4)	25 (5)
Peak grip aperture: Time (ms)	724 (121)	673 (113)	612 (98)	509 (80)
Relative value (%)	64 (8)	62 (8)	68 (9)	57 (8)
Amplitude (mm)	122 (13)	62 (13)	94 (30)	54 (7)

Note. Each value is the interparticipant mean. The standard deviation is shown in parentheses. For temporal values, the percentage relative value (expressing the absolute value as a percentage of movement duration) is shown below the absolute value in ms. For the PG → WHP/PG conditions, only the results for the five "single-grip" younger participants are presented (see text for details).

turbed, the peak grip aperture of older participants was usually more than 100 ms later than that of younger participants (see Table 3).

Seven of the 12 younger participants showed a double-grip pattern in response to the PG → WHP perturbation. Figure 4 shows examples of this doubled-grip aperture as compared with the single pattern. This doubling has previously been described in detail (Castiello et al., 1993). Of note here is that none of the older participants showed a double hand opening and closing

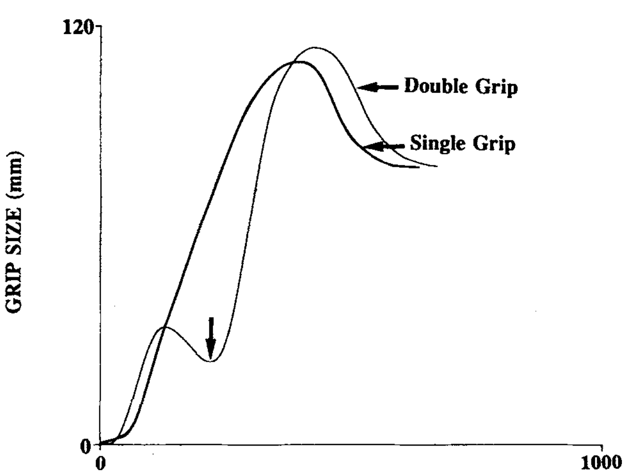

Figure 4. A comparison of the grip aperture profile obtained from one trial of a single-grip participant (D. M.) and one trial of a double-grip participant (J. B.). The vertical arrow indicates the onset of the second grip aperture.

sequence. Also of interest is that the peaks of arm-transport velocity and deceleration were greater for the double-grip than for the single-grip participants. For the analysis of the PG → WHP/PG conditions, only the manipulation component results for the 5 single-grip participants were used for the comparison with those from the 12 older participants. A test of homogeneity was performed to avoid heterogenous variability due to unequal sample size.

Despite the slower execution by the older participants, the temporal patterning of the manipulation component showed perturbation responses that resembled those of the younger participants. For the WHP → PG/WHP conditions, significant type of trial effects were found for the time of peak grip aperture: absolute $F(1, 22) = 38.23$, $p < .0001$; relative $F(1, 22) = 88.32$, $p < .0001$. Peak grip aperture for the perturbed WHP → PG trials of the older participants (562 ms, 53%) was earlier than that for nonperturbed trials (650 ms, 66%). This anticipation was also found for the younger participants (459 and 55% and 544 and 66%, respectively), and representative examples for both groups are shown in Figure 2 (bottom row). With the opposite perturbation from PG → WHP/PG, the older participants again showed a temporal reorganization of the movement in response to perturbation that was similar to that of the 5 single-grip participants. There were significant type of trial effects for the time of index finger specification: absolute $F(1, 17) = 9.48$, $p < .01$; relative $F(1, 17) = 6.03$, $p < .05$. This time was earlier for the perturbed PG → WHP trials of both groups than for the nonperturbed PG trials. For the older participants, specification occurred at an average of 232 ms (20%) for perturbed trials, but at 248 ms (24%) for nonperturbed trials (see Table 3). For the younger participants, these times were 170 ms

(20%) and 210 ms (25%) for the perturbed PG → WHP and the nonperturbed PG trials, respectively. Significant type of trial effects were also found for the time of peak grip aperture: absolute $F(1, 17) = 18.65, p < .001$; relative $F(1, 17) = 10.11, p < .01$. As shown in Figure 3, the peak is clearly later for perturbed (dotted line) than for nonperturbed trials. For the older participants, the mean time of peak grip aperture was 724 ms (64%) for the perturbed PG → WHP trials and 673 ms (62%) for the nonperturbed PG trials (see Table 3). For the younger participants, these values were 612 ms (68%) and 509 ms (57%) for the perturbed and nonperturbed trials, respectively.

Temporal Coupling Between Components

Of interest is that perturbation did not disrupt the coordination between the transport and manipulation components of the older participants. Correlations between the peak of arm deceleration (transport) and the peak of grip aperture were significant for all types of trials: perturbed WHP → PG trials, r range = .81–.90, $ps < .0001$; nonperturbed WHP trials, r range = .87–.95, $ps < .0001$; perturbed PG → WHP trials, r range = .67–.74, $ps < .05$; and nonperturbed PG trials, r range = .62–0.7, $ps < .05$. In both cases, the correlation value of the collapsed data for the perturbed trials did not differ from that for the nonperturbed trials. The younger participants showed weak or absent correlations for the perturbed trials. For the perturbed WHP → PG trials of this group, the range of correlation values was from .52 to .58, $p < .05$, and the correlation value of the collapsed data was significantly lower than the corresponding value for the older participants $p < .05$. With the opposite perturbation, the younger participants showed no significant correlations between the two components, and this disruption to intercomponent coordination was irrespective of whether the participants performed a double grip.

Discussion

This study assessed the ability of older and younger participants to respond to an unexpected change of object size during a reach-to-grasp movement. The results indicate that older participants showed quite a similar pattern of movement in response to perturbation as that of the younger participants. However, generally, the motor output of the older participants can be described as more cautious or conservative.

The movement patterning of older participants (< 70 years) appears to be largely preserved. At the observational analysis level, older participants showed the typical perturbation response of a change from PG to WHP, or vice versa. There were no obvious performance errors such as knocking over the target objects or dysmetria. At the more subtle kinematic analysis level, the temporal and spatial organizations of the reaching (transport) and grasping (manipulation) components also showed a perturbation response that resembled that of younger participants and that corresponded to results from previous perturbation studies of younger participant groups (Castiello et al., 1991, 1992, 1993; Paulignan, Jeannerod, et al., 1991).

As would be expected by perturbing target object size, the kinematics of the manipulation component were altered. For example, hand aperture was less for perturbed trials from WHP to PG than for nonperturbed WHP trials. This indicates that the WHP grasp was not fully expressed; rather, it was interrupted, presumably so that the PG could be performed. This is also supported by the findings, again for both groups, that the temporal setting of this peak aperture was earlier for the perturbed trials. With the opposite perturbation from PG to WHP, such kinematic anticipation was also evident with the parameter "specification for precision grip," that is, the time at which the index finger began to show a trajectory independent of that of the more ulnar digits. This parameter was earlier for the perturbed PG to WHP trials than for the nonperturbed PG trials. This indicates that older participants, like younger participants, actively modified the output so that the first grasp of PG was processed as quickly as possible before executing the final WHP. The average specification time of the perturbed trials of the older participants (232 ms) was 62 ms later than that for the younger participants. Nevertheless, it was still quite a prompt response. The response of older participants is compatible to the visuomotor delays reported for the transport component in previous double-step perturbation paradigms of object extrinsic properties (Gentilucci et al., 1992; Paulignan, MacKenzie, et al., 1991; Prablanc & Martin, 1992; Scarpa & Castiello, 1994), and it is greater than the minimum time estimated for closed-loop feedback influences (Evarts & Tanji, 1976; Lee & Tatton, 1975; Nashner & Berthoz, 1978; Zelaznik, Schmidt, Gielen, & Milich, 1983).

Organization of the transport component is also affected by a visual size perturbation (Castiello et al., 1992, 1993). The finding that older participants showed such changes indicates that they, like younger participants, used feedback information about the object size perturbation to modify not only the patterning of the manipulation component, but also that of the anatomically proximal transport component. An example of such modification can be seen with the parameter of peak deceleration. For both groups, the timing of this parameter was absolutely and relatively earlier for perturbed than for nonperturbed trials. As has been previously suggested, the neural processing for each of these two components is thus interdependent (Castiello et al., 1992, 1993; Gentilucci et al., 1991; Jeannerod, 1981, 1984; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990; Wallace & Weeks, 1988; Wing, Turton, & Fraser, 1986). This interdependence is maintained with age; in fact, as explained later, it may become stronger with age.

The main differences between older and younger participants lie in the approach phase of the movement, that is, the period when the hand is honing in on the target. Without perturbation, older participants are already known to show longer deceleration times (Bennett & Castiello, 1994). This was again evident in the current study. Looking, for example, at the nonperturbed PG movements, the deceleration time of arm approach was, on average, 276 ms greater for the older than for the younger participants. Such an extension also explains why the overall movement duration was so much longer for this group. Furthermore, in response to this generally longer deceleration time, older participants showed yet a further increase to this later part of the movement with perturbation. This increase to deceleration time was small (49–67 ms, 2% of movement duration), but presumably gave just that little bit of extra time for error correction and precise placement of the digits about the object.

In line with the view of Welford (1982), the older participant thus appeared to place greater emphasis on end-task accuracy and may have been more concerned about committing an error (Salthouse, 1979, 1985).

The strong correlations between temporal events of each component further demonstrate that older participants had a more conservative movement approach. Despite having to rapidly change motor output, coordination between the reaching and the grasping movements was regained to ensure that the point of maximum arm deceleration was temporally coupled to that of maximum hand aperture (Jeannerod, 1981, 1984). This suggests again that reorganization of the transport component is dependent on concurrent changes in the manipulation component. The younger participants showed a more variable and flexible pattern, which offered a greater number of motor output options when the system was stressed. Temporal coupling between the transport and manipulation components was not as strong as that found for older participants. This was particularly evident for the perturbation from PG to WHP where no correlations were found between the two components. Transport and manipulation are thus activated in parallel but without obvious indication of temporal coupling; reorganization of one component is clearly not dependent on that of the other. The greater flexibility of younger participants is also supported by the finding of a double-grip pattern (50% of younger participants), in association with a more rapid arm movement and larger accelerative and decelerative bursts, with perturbation from PG to WHP. It is as if the greater movement speed was a hindrance to a premature braking of the first grip pattern; precision grip was thus executed almost completely before the second grasp pattern could commence. The performance of this double-grip pattern, nevertheless, did not disturb the success of the final motor output.

It is interesting to speculate how the results of this study relate to the incidence of accidents for older people. It has been consistently demonstrated that the rate of falls for people older than 65 years is approximately 25–35% (Campbell, Borrie, & Spears, 1989; Gryfe, Amies, & Ashely, 1977; Nickens, 1985; Tinetti, Speechley, & Ginter, 1988). Also, the rate of traffic accidents is higher for older than for younger participants (Huston & Janke, 1986). A number of factors have been identified as potential contributors to such accidents (e.g., see Kline et al., 1992; Stelmach & Nahom, 1992; Studenski, Duncan, & Chandler, 1991; Tinetti, Williams, & Mayewski, 1986). One factor that has received little attention relates to how rapidly the older person is able to unexpectedly change motor output. If the ability to perform such rapid adaptations is slow or impaired, the likelihood of an accident would significantly increase. Studies of age-related changes in the ability to respond to unexpected perturbations of balance have indicated, for example, that older participants (ages 61–78 years) show slower electromyographic responses of distal lower limb muscles and intermittent reversals in the normal disto/proximal sequence of leg muscle contractions (Manchester, Woollacott, Zederbauer-Hylton, & Marin, 1989; Woollacott, Shumway-Cook, & Nashner, 1986).

It is obviously difficult to relate confidently the current study to the incidence of accidents. What our results indicate, however, is that the response of older participants to perturbation is slower and takes longer. This is evidenced by the later time for "specification for precision grip" and the greater deceleration times and movement durations. Furthermore, even though the patterning of the perturbation response was largely similar to that of the younger participants, there were isolated examples that could indicate the beginnings of a subtle breakdown even at the level of movement organization. For example, the amplitude of the peak of arm velocity consistently shows a different pattern of results when comparing the older with the younger participants. The peak of grip aperture for the older participants was exaggerated for the perturbed PG to WHP trials when compared with the results for the younger participants. In addition, the movement tended to be less flexible. For example, even if there was no obvious temporal coordination between the components, younger participants still performed a successful movement. For the older participants, such lack of temporal coupling may have entirely disturbed organization of the second unexpected movement and resulted in error. Rather than incur such a response, the older participants thus could have adopted a more rigid approach. With age, the resultant lack of movement experimentation and flexibility during movement reorganization could lead to a gradual decrease of output options under accidental conditions.

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