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Aging and Tennis Playing in a Coincidence-Timing Task With an Accelerating Object: The Role of Visuomotor Delay

Régis Lobjois, Nicolas Benguigui, and Jean Bertsch

The purpose of the present study was to determine whether playing a specific ball sport, such as tennis, could maintain the coincidence-timing (CT) performance of older adults at a similar level to that of younger ones. To address this question, tennis players and nonplayers of three different age ranges (ages 20–30, 60–70, and 70–80 years) performed a simple CT task consisting of timing their response (pressing a button) to coincide with the arrival of a stimulus at a target. The stimulus moved at either an accelerating, constant, or decelerating velocity. As expected, all participants were affected by the velocity manipulation, which led to late and early responses to accelerating and decelerating stimuli, respectively. Whereas this response bias was increasingly pronounced with advancing age in nonplayers, no difference was found among player groups of different ages. Finally, we showed that the length of the visuomotor delay could explain the effect of nonconstant velocities.

Key words: age, perceptuomotor processes, response timing

Older adults generally have more difficulty than younger ones adapting their actions to the displacement of a moving object in real-world tasks, such as grasping (e.g., Bennett & Castiello, 1995) or crossing a street (e.g., Oxley, Fildes, Ihsen, Charlton, & Day, 1997). One can assume that part of the age-related differences in these tasks comes from less efficient coincidence-timing (CT) processes (e.g., Stelmach & Nahom, 1992). To be successful in CT actions, such as catching or hitting balls, the individual must determine when a moving object will reach a target point in space and tune his or her action to the object's motion based on temporal information (e.g., Tresilian, 1995). In simple CT tasks, which consist of timing an impulse type of response (pressing a button) to coincide with the moving object's arrival at the target, women and men over the age of 60 years generally perform with greater overall error and variability than do younger ones. Furthermore, older adults usually produce late responses (Haywood, 1980; Meeuwsen, Goode, & Goggin, 1997). Although this result has been explained mainly by age-related declines in perceptual processes (e.g., Haywood, 1980), the effects of age on perceptuomotor processes should not be overlooked.

To better understand the perceptuomotor problems of older adults, we need to examine the mechanisms involved in CT tasks. Perfect accuracy in such tasks requires issuing the motor-response command before the moving object arrives at the target (Benguigui, Ripoll, & Broderick, 2003). To plan this action, the individual has to take into account his or her own visuomotor delay (VMD; i.e., the perceptuomotor-process inertia time between the visual registering of information and the effecting of the action; e.g., Carlton & Carlton, 1987; Tresilian, 1993). As VMD is known to increase with motor-task complexity (Carlton, 1992; Zelaznik, Hawkins, & Kisselburgh, 1987) and be longer in older adults (Bennett & Castiello, 1995; Warabi, Noda, & Kato, 1986), one can assume that the older adult lateness observed by Haywood (1980) and

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Régis Lobjois is with the Psychology Laboratory at the National Institute of Research on Transportation and Safety, Arcueil, France. Nicolas Benguigui and Jean Bertsch are with the Center for Research in Sport Sciences at the University of Paris-Sud.

Meeuwsen et al. (1997) comes from difficulty integrating an increasing VMD into the response at execution time.

In contrast to these negative effects of aging, there is evidence that older adults remain able to perform well under certain circumstances, such as when they exercise or do physical activities (like running, swimming, or cycling). Some studies have shown that physically active older adults are more accurate and consistent in CT tasks than less active ones (Christensen et al., 2003; Del Rey, 1982). However, the negative effects of aging in active older adults are still observable, because their performance remains lower than that of younger adults (Haywood, 1980). If age deficiencies in CT tasks are moderated only by physical activities, one can assume that aging effects could be eliminated by a specific activity, such as a ball sport, in which CT actions are common.

One way to investigate this question would be to test older adults, who play or do not play a ball sport, using a CT task with accelerating velocities. It has been shown that velocity variations make CT tasks more difficult and require accurate tuning (e.g., Benguigui et al., 2003; Ripoll & Latiri, 1997). The difficulty comes from the observer's inability to use acceleration information from the moving object to estimate the time-to-contact (TTC), that is, the time remaining before the object reaches the observer or a particular point in space (Kaiser & Hecht, 1995; Lee, Young, Reddish, Lough, & Clayton, 1983). Instead, first order information, such as the optical variable tau[1], may be used to estimate a first order TTC (TTC1). But TTC1 does not account for acceleration (see the gap between TTC1 and real TTC in Figure 1) and, therefore, does not define the real temporal relationship between the observer and the object. In CT actions that depend on the inertia time of the perceptuomotor system (i.e., VMD), TTC1 information is picked up at some time before the moving object arrives at the target (which corresponds to the individual's VMD). Due to the discrepancy between TTC1 and real TTC before stimulus arrival, CT errors will be large (Benguigui & Ripoll, 1998). Furthermore, the longer the VMD, the greater the errors will be. This can be explained by the fact that information is picked up at points where the difference between TTC1 and real TTC is increasing (see Figure 1). This means that all individuals should be affected by nonconstant velocities. Sedentary older adults, who have longer VMDs, should make more errors with accelerating and decelerating motion, because they have to initiate their responses sooner than younger adults. However, older adults who play a ball sport on a regular basis may be able to minimize such errors, because they maintain a short VMD. These hypotheses were addressed in two experiments in which we examined (a) the effects of nonconstant velocities on CT accuracy as a function of age and tennis playing, and (b) the link between VMD length (measured in a stop-signal task) and errors at nonconstant velocities in a CT task.

Method

Participants

Three age groups (ages 20–30, 60–70, and 70–80 years) with two different levels of tennis experience (players and nonplayers) participated in two experiments (see Table 1 for the mean age and standard deviation of each group). All groups contained eight male participants. As is typically the case in research on aging (e.g., Fleury & Bard, 1985; Haywood, 1980; Meeuwsen et al., 1997), we selected only men to avoid a possible gender effect and minimize the heterogeneity of the groups. The younger groups were composed of students and the older groups of retired individuals living on their own. By comparing two different older adult age groups (ages 60–70 and 70–80 years), our aim was to extend previous results in which only one older group was tested (e.g., Fleury & Bard, 1985; Haywood, 1980; Meeuwsen et al., 1997) to gain insight into CT performance changes in the course of aging.

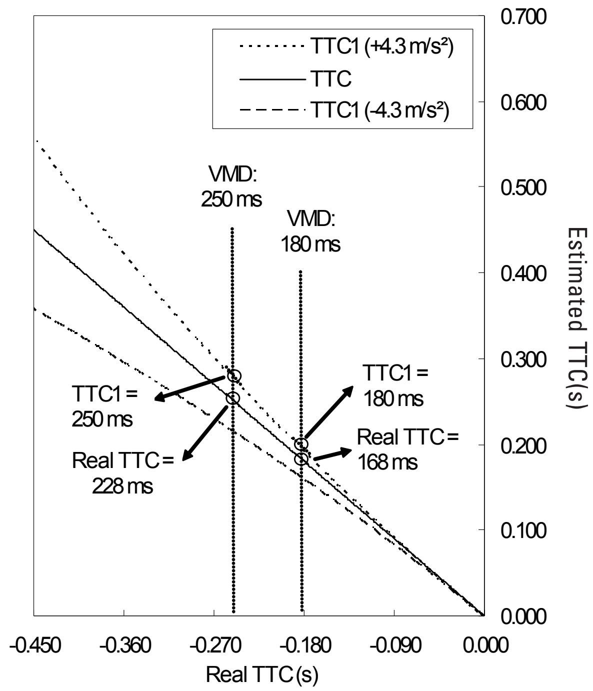

Figure 1. Illustration of the gap between real time-to-contact (TTC) and TTC1 determined from first order information (estimated TTC) in the accelerating (+4.3 m/s^2) and decelerating (-4.3 m/s^2) conditions, as a function of real TTC (these conditions were used in Experiment 1). A participant with a visuomotor delay of 250 ms and assumed to use TTC1 ought to initiate his response for a TTC1 value equal to 250 ms. Given that real TTC was 228 ms when TTC1 was 250 ms in the accelerating velocity condition, an error of 22 ms could be predicted. In contrast, a participant with a VMD of 180 ms ought to respond late with an error of 12 ms.

Tennis was chosen as the ball sport for two main reasons. First, ball velocity is rarely constant in tennis due to variable muscular actions, spins, air resistance, or ball impact. Perceptuomotor processes, particularly VMD, are, therefore, needed on every ball hit to update the relationship between the ball's ever changing trajectory and the player's motor response. Second, tennis is probably the most common ball sport played across the life span, which made it possible to recruit experienced older players with a long playing history.

To be eligible for the study, the "players" were required to have played tennis between 2 and 4 hours a week for at least 10 years (see Table 1). With this much practice, one can assume that the players have repeated the concerned perceptuomotor processes thousands of times. All the players were active in tennis clubs, with a significant history of regular playing, but neither the younger nor the older players were of professional caliber. Our aim was to recruit tennis players who played on a regular basis and had experience but were not "experts" in the game. In other words, our goal was more to study the effects of "social" playing, like that done by most older tennis players, than expert playing. The nonplayers had no previous or current experience in tennis or other ball games.

All participants were right-handed and reported normal or corrected-to-normal vision. None reported any neurological disorders or ocular pathologies, such as glaucoma, cataract, or macular degeneration. All signed an informed consent form before taking part in the study.

Experiment 1: CT Performance at Nonconstant Velocities

Design and Task

The experimental display was composed of a runway of red light emitting diodes (LEDs) that simulated the displacement of a moving object from left to right, ending at a target. The apparent continuous motion was generated on a 4-m simulator by the sequential switching on of 200 LEDs placed at 2-cm intervals.

Participants sat 4 m away from the apparatus, facing the target. Once informed of the appearance point of the stimulus, they started each trial by pressing a button with their preferred hand. To respond, they were required to press the button a second time to make their response coincide with the arrival of the moving object at the end of the runway. The time between the participant's response and the illumination of the last LED was the measure of response accuracy (in ms).

Participants performed the task in each of three velocity conditions: a constant-acceleration velocity (+4.3 m/s^2, from 2.95 to 5.88 m/s), a constant velocity (4.38 m/s), and a constant-deceleration velocity (-4.3 m/s^2, from 5.81 to 2.88 m/s). The viewing time of the moving stimulus was identical (680 ms) in all conditions. Note that the final velocities in the three conditions were different. To ensure that the expected effect of nonconstant velocities was due to the velocity variation (and not the final velocities), two "control" conditions with a constant velocity were added (5.88 and 2.88 m/s, with the same viewing time). The control conditions were used to compare constant to nonconstant velocities ending with the same arrival speed.

Procedure

Following an explanation by the experimenter, a training session was conducted consisting of 15 randomly presented trials with three different velocities (two nonconstant, +1.9 m/s^2 and -1.9 m/s^2, and one constant). During the training session, feedback about temporal accuracy (size and direction of error, in ms) was given to the participants after each trial. During the experimental session, each participant performed 8 trials per velocity condition (for a total of 24 trials[2]), and

Table 1. Age and tennis playing measures in each group

	Age group	Age (years)		Tennis playing: Years		Tennis playing: Hours per week	
		M	*SD*	*M*	*SD*	*M*	*SD*
Players	20–30	22.9	2.54	15.3	3.65	3.50	0.76
	60–70	66.0	3.73	30.9	16.1	3.25	1.04
	70–80	75.3	2.74	37.0	18.9	3.13	0.99
Nonplayers	20–30	25.9	3.35	—	—	—	—
	60–70	64.7	1.62	—	—	—	—
	70–80	74.0	2.66	—	—	—	—

Note. M = mean; *SD* = standard deviation.

the velocity order was randomized. Corrective feedback (in ms) was given after each trial during data collection. The two control conditions were presented in one block of 16 trials at the end of the nonconstant-velocity session, using an identical experimental procedure.

For each participant and each condition, constant error (CE) and variable error (VE) were calculated. CE was the algebraic mean of the error, which was equal to the difference between the actual arrival time and the participant's response. CE scores indicated the directional bias of the responses (early responses had a negative sign, late responses a positive sign). VE was equal to the standard deviation of the errors and indicated the response dispersion[3]. An analysis of variance (ANOVA) was carried out on CE and VE, with age group (20-30, 60-70, and 70-80) and tennis playing (players and nonplayers) as between-participant factors and velocity condition (accelerating, constant, and decelerating) as a within-participant factor. Significance was set at .05. The effect size (η^2) was also computed. Significant differences were detected using a Newman-Keuls post hoc test when necessary. A similar analysis compared nonconstant to constant velocities ending with the same arrival speed (i.e., +4.3 m/s^2 vs. 5.88 m/s and -4.3 m/s^2 vs. 2.88 m/s).

Results

As expected, the error analysis on CE revealed a main effect of velocity, $F(2, 84) = 338.32$, $\eta^2 = .88$. Responses were late when the stimulus was accelerating (M = 25 ms), early when it was decelerating (M = -24 ms), and slightly biased when its velocity was constant (M = 3 ms). The results also indicated significant two-factor interactions between age group and velocity, $F(4, 84) = 6.26$, $\eta^2 = .22$, and between tennis playing experience and velocity, $F(2, 84) = 30.57$, $\eta^2 = .42$. The three-factor interaction between age, playing experience, and velocity also reached significance, $F(4, 84) = 4.93$, $\eta^2 = .18$. This interaction is depicted in Figure 2. In players, the post hoc analysis yielded no age-related difference in any of the velocity conditions. However, in nonplayers, both older groups were significantly different from the younger one in the accelerating velocity condition but not in the decelerating condition. The absence of an age effect in the decelerating condition may be due to the fact that the younger group was more likely to produce earlier CT responses than the other groups, as shown by their systematic negative CE responses at all constant velocities (M = -5, -12, and -7 ms, for the constant velocity and the two control conditions, respectively). This tendency may have affected their performance in the decelerating velocity condition, thus cancelling the age-related effect. The means for each group (as well as standard deviations) are given in Table 2.

Two additional analyses were performed to make sure the velocity effect was due to the velocity variation and not the different final velocities in the nonconstant conditions. A first ANOVA (Age$_3$ x Tennis Playing$_2$ x Velocity$_2$) compared CE in the decelerating condition to CE in a constant velocity condition in which the velocity (2.88 m/s) was equal to the final velocity of the decelerating condition. This analysis revealed that for all age groups the response bias was not as great at the constant velocity as in the decelerating condition, $F(1, 42) = 130.52$, $\eta^2 = .75$ (see Table 2). The second ANOVA (Age$_3$ x Tennis Playing$_2$ x Velocity$_2$) confirmed a significant difference between CE in the accelerating condition and CE in the constant velocity condition in which the velocity (5.88 m/s) was equal to the final accelerating velocity, $F(1, 42) = 72.26$, $\eta^2 = .63$ (see Table 2). These results support the conclusion that the observed biases were, in fact, due to the velocity variation and not to the final velocities.

Last, an analysis of variance on VE revealed a main effect of age, $F(2, 42) = 12.51$, $\eta^2 = .37$. VE was higher for the 70–80 year-olds (M = 31 ms) than for the 60–70-year-olds (M = 24 ms) and the 20–30-year-olds (M = 21 ms), who did not differ from each other. There was no other main effect or interaction on VE.

Experiment 2: VMD and CT Errors in the Nonconstant Velocity Conditions

This experiment was designed to measure the VMD length of each participant, using a stop-signal task, and explore the link between VMD and CT accuracy in nonconstant velocity conditions[4].

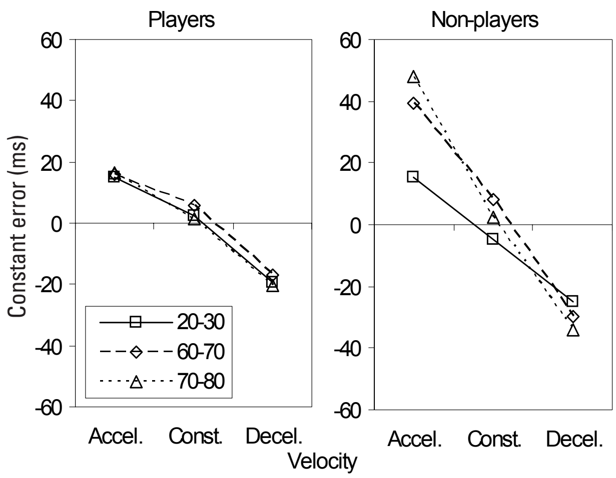

Figure 2. Constant error (ms) as a function of age group (ages 20–30, 60–70, and 70–80 years) and velocity (accelerating, constant, and decelerating) for tennis players and nonplayers.

Design and Task

The experimental display was the moving object simulator used in Experiment 1. The participants sat as above, 4 m away from the apparatus, facing the target. A stop-signal procedure (e.g., Logan, 1994) was used to measure VMD. Participants were asked to produce two kinds of responses, depending on the stimulus trajectory. Stimulus movement along the trajectory was either visible until the stimulus arrived at the target or occluded before it arrived. When the trajectory was visible up to the target, participants were required to press a button at the same time the stimulus arrived at the target, as in the previous experiment. Trials with occlusion were called catch trials. On catch trials, the participants were asked to inhibit their response (not respond). The occlusion time (duration) was varied across trials between 150 and 330 ms in steps of 20 ms (for a total of 10 occlusion times).

With this procedure, the probability of responding to a catch trial was a function of occlusion time and VMD length. In catch trials in which the occlusion occurred before the "last" information used to produce the response was picked up, participants ought to be able to inhibit their responses. In these cases, VMD was shorter than TTC at occlusion time. In contrast, in trials in which the occlusion occurred after the pick up of the "last" information used to produce the response, participants should no longer be able to inhibit their responses. In these cases, VMD was longer than TTC at occlusion time. The overall probability of error (i.e., pressing the button when the stimulus trajectory was occluded) should, therefore, be higher for participants with a longer VMD.

For all trials, the apparent stimulus moved at a constant velocity (2 m/s), and the viewing time for each complete trajectory was 1 s. Note that only one velocity was used in this experiment, because VMD length is known to be independent of stimulus velocity (e.g., Benguigui et al., 2003).

Procedure

Participants were told that the ability to inhibit their response was as important as their ability to press the button accurately when the stimulus was not occluded. This explanation was given to ensure that they would not focus on one part of the task and neglect the other. The participants then performed one 20-trial practice block that included four catch trials. For the catch trials, the stimulus was occluded 300 ms before it reached the end of the runway. Corrective auditory feedback was provided for CT accuracy (in ms) and response inhibition on catch trials. During the testing session, the participants performed 150 CT trials and 5 catch trials per occlusion time (for a total of 50 catch trials). The trials were divided into five blocks of 40 trials, and catch trials occurred 25% of the time in each block (i.e., 10 times) equally often at each occlusion time (i.e., once per occlusion time per block). The location and presentation order of each occlusion time in a block were randomly distributed across groups, participants, and blocks. Corrective feedback was provided.

Data Analysis

Psychometric curves were obtained for each participant from the responses to catch trials, as a function of occlusion time (see Figure 3 for an illustration). The response probability ranged between 1 (participant always responding for occlusion times shorter than VMD) and 0 (participant never responding for occlusion times longer than VMD). Logistic functions were fit to the psychometric curves for each participant. The logistic function is a classical psychophysical function and a convenient model for psychometric curves describing human performance on sensory tasks (e.g., Treutwein & Strasburger, 1999). To determine each participant's VMD, we used the mean of the logistic function, as typically done in

Table 2. CE (ms) for the different groups in the accelerating, constant, and decelerating velocity conditions, and in the control conditions (2.88 and 5.88 m/s)

	Age group years	Decelerating condition		Constant velocity (4.38 m/s)		Accelerating condition		Control condition 2.88 m/s		Control condition 5.88 m/s	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Players	20–30	-19	10	2	12	15	13	3	14	-7	9
	60–70	-17	9	6	13	16	11	1	11	10	11
	70–80	-21	9	1	10	16	11	-1	12	3	9
Nonplayers	20–30	-25	9	-5	10	15	5	-12	4	-7	12
	60–70	-30	13	8	15	39	8	0	16	18	8
	70–80	-34	11	2	13	48	10	-7	10	24	10
Mean		-24	12	2	12	25	16	-2	12	7	15

Note. M = mean; *SD* = standard deviation.

such experiments (e.g., Slater-Hammel, 1960). The mean was estimated by calculating the occlusion time at which participants inhibited their responses 50% of the time (i.e., center of the fit function; see Figure 3). To avoid the possibility of over- or underestimation of VMD due to nonzero responses on the CT task, VMD for each participant was obtained by adding his CE, when no catch trials were presented, to the 50% point.

Results

The analysis conducted on VMDs (Age_3 x $Experience_2$) revealed that VMD increased significantly with age, $F(2, 42) = 8.83$, $\eta^2 = .29$. VMD was 196 ($SD = 15$ ms), 217 ($SD = 23$ ms), and 225 ms ($SD = 25$ ms) in the three age groups, respectively. This increase was significantly reduced by tennis playing, $F(2, 42) = 9.08$, $\eta^2 = .17$, because tennis players had shorter VMDs ($M = 188$, 207, and 214 ms, with $SD = 8$, 24, and 17 ms for the 20–30, 60–70, and 70–80-year-old players, respectively) than did nonplayers ($M = 204$, 225, and 236 ms, with $SD = 16$, 19, and 29 ms for the 20–30, 60–70, and 70–80-year-old nonplayers, respectively). However, the interaction between age group and tennis playing was not significant, $F(2, 54) = 0.01$, $p = .98$.

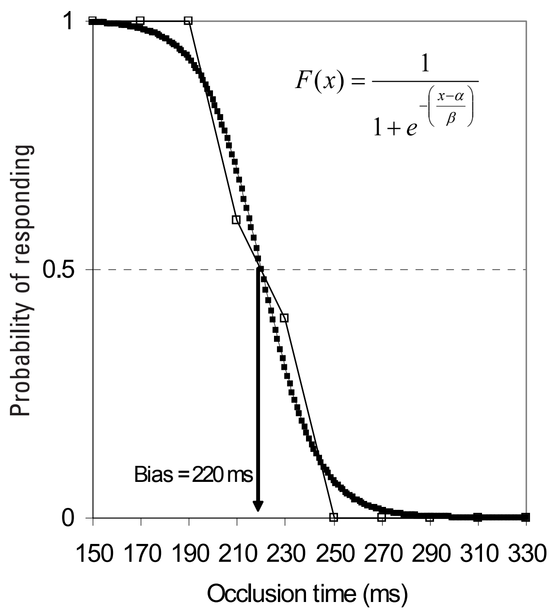

Figure 3. Erroneous responses of one nonplayer in the 60–70-year-old age group, as a function of the occlusion time before contact. This result pattern corresponds to a typical psychometric curve. A logistic function was used to fit the nonlinear curve to the data generated by binary responses that followed a sigmoid (or S-shaped) curve. The logistic function was:

$$F(x) = \frac{1}{1+e^{-\left(\frac{x-\alpha}{\beta}\right)}}$$

From this function, the center (a) and slope (b) of the curve, basic performance descriptors, can be estimated. The center of the fitted curve provides a measure of the mean of the psychometric curve. This corresponds to the argument for a function value of 0.50. For this participant, the mean was 220 ms, corrected to a visuomotor delay of 239 ms after adding his constant error (19 ms).

VMD-Based Error Prediction in the Nonconstant Velocity Conditions

Errors in the nonconstant velocity conditions of Experiment 1 were predicted on the basis of two assumptions: participants were assumed to (a) pick up information at a time corresponding to their VMD, and (b) use TTC1 instead of TTC. Errors were determined by calculating the difference between TTC1 and real TTC when TTC1 was equal to VMD (see Figure 1 for an illustration with the accelerating velocity). The predicted errors were then compared to the actual ones. Because of a possible bias of some participants on CT tasks (i.e., a general tendency to respond late or early), an overall error (OE) was calculated for the predicted and actual data. OE was equal to the difference between the CEs in the accelerating and decelerating conditions. These values are presented for each group in Table 3. To determine whether VMD could account for the CT bias, a regression analysis was performed with predicted OE as the independent variable and actual OE as the dependent variable. The regression analysis yielded a significant relationship between the predicted and actual results, $r^2 = .37$, $F(1, 44) = 26.47$, $p < .0001$[5] (see Figure 4). Note that this correlation was still significant when the age effect was partialed out. This finding confirms our hypothesis that VMD is a relevant factor in explaining CT responses.

Discussion

As hypothesized, accuracy in coincidence timing was clearly affected by the velocity variation. All participants responded too late in the accelerating velocity condition and too early in the decelerating velocity condition. The effect of nonconstant velocities was additionally supported by the fact that the accelerating conditions differed significantly from the constant velocity conditions whose velocity matched the final velocity in the nonconstant conditions. This result pattern is in line with recent data showing that CT response bias increases when velocities are either accelerating or decelerating (e.g., Benguigui et al., 2003).

With regard to aging, the results confirmed previous studies showing that older adults have trouble synchronizing their responses with moving objects (Haywood, 1980; Meeuwsen et al., 1997). They also showed that older adults had more trouble than their younger counterparts in the accelerating and decelerating conditions. In addition, this age-related impairment, whether at nonconstant or constant velocities, continued to rise as age rose from 60-70 to 70-80 years. These results are only applicable to men, however, because there were no female participants. Given that studies on how age affects CT skills have used either men (e.g., Christensen et al., 2003; Fleury & Bard, 1985; Haywood, 1980) or women (e.g., Del Rey, 1982; Meeuwsen et al., 1997), comparing participants of the two genders would provide a more general understanding of the effects of aging on CT actions.

Perceptual deficits are usually proposed to account for the difficulty of older adults in CT tasks (Haywood, 1980; Meeuwsen et al., 1997). However, in this study, the older adults cannot be said to have had more trouble using acceleration information, because the younger adults did not use acceleration either, as revealed by a similar response bias in the nonconstant velocity conditions for all age groups (see also Benguigui et al., 2003). Instead, we suggest that older adults are affected more by nonconstant velocities because of a perceptuomotor deficit (i.e., their greater VMD). This hypothesis was supported by the second experiment in which older adults were found to have a longer VMD than younger ones, as noted by Bennett and Castiello (1995) and Warabi et al. (1986). It was also validated by the significant correlation between the actual errors in the nonconstant conditions (see Experiment 1) and the errors predicted on the basis of VMD.

Meeuwsen et al. (1997), who examined CT accuracy in two tasks with different motor complexity levels, already noted the perceptuomotor deficit identified in this study. Two age groups of young (*M* age = 22.9 years) and older (*M* age = 75 years) adults were tested in both a simple switch-pressing task and a more complex hitting task. The latter task consisted of using a stick to hit a barrier so that it would press a microswitch at the same time a stimulus arrived at a target. Whereas younger adults performed the two tasks in the same way, the older participants' response bias was greater in the CT task and increased with motor complexity, suggesting perceptuomotor and motor impairment. These deficits can be compared to those found in a study by Bennett

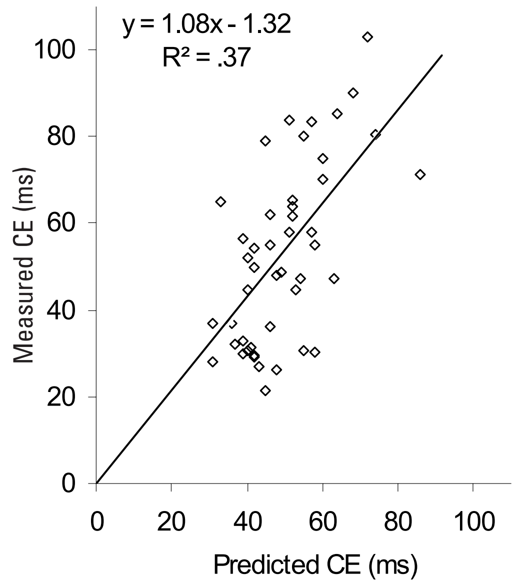

Figure 4. Correlation (regression line and r^2) between measured error and error predicted on the basis of visuomotor delay. These values correspond to the differential between constant errors (CEs) for accelerating stimuli and CEs for decelerating stimuli, which is one way of accounting for the extent of the nonconstant velocity effect.

Table 3. Predicted CE (calculated from VMD) and actual CE for each group in the accelerating and decelerating conditions

	Age group (years)	Predicted CE from the VMD length CE-Acc	CE-Dec	OE*	Actual CE CE-Acc	CE-Dec	OE[a]
Players	20–30	13	-26	39	15	-19	34
	60–70	15	-31	46	16	-17	33
	70–80	17	-34	51	16	-21	37
Nonplayers	20–30	15	-30	45	15	-25	40
	60–70	18	-37	55	39	-30	69
	70–80	20	-41	61	48	-34	82
Mean	16	-33	49	25	-24	49	

Note. CE = constant error; VMD = visuomotor delay; CE-Acc = constant error in the accelerating velocity condition; CE-Dec = constant error in the decelerating velocity condition; OE = overall error.
[a]OE corresponds to the difference between the CEs in the accelerating and decelerating conditions. Note that the mean OE predicted from VMD (49 ms) is exactly equal to the mean OE observed in the data.

and Castiello (1995), who used a stationary-object prehension task and showed that older adults needed more time to adapt their movement to unexpected changes.

In contrast to these negative effects of age, no difference on response timing appeared between the younger and older tennis players when nonconstant velocities were presented. This result is consistent with data showing that playing a sport (such as tennis or golf; e.g., Spirduso & Clifford, 1978), doing physical exercise (e.g., Rikli & Edwards, 1991), or practicing (e.g., Light, Reilly, Behrman, & Spirduso, 1996) may slow down age-related effects on a number of sensorimotor functions. Physical exercise has also been shown to reduce the effects of age on CT performance in older adults who remain physically active (Christensen et al., 2003; Del Rey, 1982; Haywood, 1980). Our study showed in addition that the typical effects of aging can be completely eliminated by lifelong practice of an activity involving CT processes. Similar results have been reported previously, but only in older adults who were regarded as experts in their activity (e.g., typing: Bosman, 1993; chess or bridge playing: Charness & Bosman, 1990; piano playing: Meinz, 2000). The fact that the participants we selected were not experts but only recreational players should be considered in view of improving the well being of older adults.

The question that arises from these results concerns the origin of sustained accuracy in older recreational tennis players. Again, the results of the second experiment provide an alternative to the classical interpretations. First, the effect of playing tennis here was that our older tennis players had shorter VMDs than our older nonplayers. Second, the significant correlation between the observed OE and the errors predicted from VMD length showed that participants who had the shortest VMDs (younger participants and older tennis players) were less affected by nonconstant velocities than older nonplayers. These data argue in favor of the idea that tennis playing has a beneficial effect on CT accuracy, because it maintains a short VMD.

In summary, our study offers the important finding that VMD plays a role in CT tasks, making it a good candidate to explain the CT response bias. Whereas previous studies focused on the well established effects of aging on perceptual processes, our findings strongly suggest that more attention should be paid to perceptuomotor processes in CT performance. With regard to the observed age effects, the present results confirm the conclusion drawn by others (Haywood, 1980; Meeuwsen et al., 1997), that older adults are impaired in tuning their responses to a moving object. In addition, we showed that older adults were also impaired when the stimulus velocity was not constant, a finding never obtained so far. Furthermore, our hypothesis, that age effects can be eliminated and not merely reduced by a ball-sport activity involving CT processes, was validated.

The encouraging relationship between aging, tennis playing, and CT accuracy should be studied in more ecological activities to promote the autonomy of older adults and find ways to maintain that autonomy as long as possible.

References

Benguigui, N., & Ripoll, H. (1998). Effects of tennis practice on the coincidence timing accuracy of adults and children. *Research Quarterly for Exercise and Sport*, *69*, 217–223.

Benguigui, N., Ripoll, H., & Broderick, M. P. (2003). Time-to-contact estimation of accelerated stimuli is based on first-order information. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 1083–1101.

Bennett, K. M. B., & Castiello, U. (1995). Reorganization of prehension components following perturbation of object size. *Psychology and Aging*, *10*, 204–214.

Bootsma, R. J., & Oudejans, R. R. D. (1993). Visual information about time to collision between two objects. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 1041–1052.

Bosman, E. A. (1993). Age-related differences in motoric aspects of transcription typing skill. *Psychology and Aging*, *8*, 87–102.

Carlton, L. G. (1992). Visual processing time and the control of movement. In L. Proteau & D. Elliott (Eds.), *Vision and motor control* (pp. 3–31). Amsterdam: Elsevier Science Publishers.

Carlton, L. G., & Carlton, M. J. (1987). Response amendment latencies during discrete arm movement. *Journal of Motor Behavior*, *19*, 333–354.

Charness, N., & Bosman, E. A. (1990). Expertise and aging: Life in the lab. In T. M. Hess (Ed.), *Aging and cognition: Knowledge organization and utilization* (pp. 343–386). Amsterdam: Elsevier Science Publishers.

Christensen, C. L., Payne, V. G., Wughalter, E. H., Yan, J. H., Henehan, M., & Jones. R. (2003). Physical activity, physiological, and psychomotor performance: A study of variously active older adult men. *Research Quarterly for Exercise and Sport*, *74*, 136–142.

Del Rey, P. (1982). Effects of contextual interference on the memory of older females differing in levels of physical activity. *Perceptual and Motor Skills*, *55*, 171–180.

Fleury, M., & Bard, C. (1985). Age, stimulus velocity and task complexity as determiners of coincident timing behavior. *Journal of Human Movement Studies*, *11*, 305–317.

Haywood, K. M. (1980). Coincidence-anticipation accuracy across the life span. *Experimental Aging Research*, *6*, 451–462.

Kaiser, M. K., & Hecht, H. (1995). Time-to-passage judgments in nonconstant optical flow fields. *Perception and Psychophysics*, *57*, 817–825.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception*, *5*, 437–459.

Lee, D. N., Young, D. S., Reddish, P. E., Lough, S., & Clayton, T. M. H. (1983). Visual timing in hitting an accelerating ball. *Quarterly Journal of Experimental Psychology*, *35A*, 333–346.

Light, K. E., Reilly, M. A., Behrman, A. L., & Spirduso, W. W. (1996). Reaction times and movement times: Benefits of practice to younger and older adults. *Journal of Aging and Physical Activity, 4*, 27–41.

Logan, G. D. (1994). On the ability to inhibit thought and action: A users' guide to the stop signal paradigm. In T. H. Dagenbach & D. Carr (Eds.), *Inhibitory processes in attention, memory and language* (pp. 189–239). San Diego, CA: Academic Press.

Meeuwsen, H. J., Goode, S. L., & Goggin, N. L. (1997). Effects of aging on coincidence anticipation timing in females. *Journal of Aging and Physical Activity, 5*, 285–297.

Meinz, E. J. (2000). Experienced-based attenuation of age-related differences in music cognition tasks. *Psychology and Aging, 15*, 297–312.

Oxley, J., Fildes, B., Ihsen, E., Charlton, J., & Day, R. (1997). Differences in traffic judgments between young and old adult pedestrians. *Accident Analysis and Prevention, 29*, 839–847.

Rikli, R. E., & Edwards, D. J. (1991). Effects of a three-year exercise program on motor function and cognitive processing speed in older women. *Research Quarterly for Exercise and Sport, 62*, 61–67.

Ripoll, H., & Latiri, I. (1997). Effect of expertise on coincident-timing accuracy in a fast ball game. *Journal of Sport Sciences, 15*, 573–580.

Slater-Hammel, A. T. (1960). Reliability, accuracy, and refractoriness of a transit reaction. *The Research Quarterly, 31*, 217–228.

Spirduso, W. W., & Clifford, P. (1978). Replications of age and physical activity effects on reaction and movement time. *Journal of Gerontology, 33*, 26–30.

Starkes, J. L. (1993). Motor experts: Opening thoughts. In J. L. Starkes & F. Allard (Eds.), *Cognitive issues in motor expertise* (pp. 3–16). Amsterdam: Elsevier Science Publishers. **[AQ: Include in text or delete.]**

Stelmach, G. E., & Nahom, A. (1992). Cognitive motor abilities of the elderly drivers. *Human Factors, 34*, 53–65.

Tresilian, J. R. (1990). Perceptual information for the timing of interceptive action. *Perception, 19*, 223–239.

Tresilian, J. R. (1991). Empirical and theoretical issues in the perception of time to contact. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 865–876.

Tresilian, J. R. (1993). Four questions of time-to-contact: A critical examination of research on interceptive timing. *Perception, 22*, 653–680.

Tresilian, J. R. (1995). Perceptual and cognitive processes in time-to-contact estimation: Analysis of prediction-motion and relative judgment tasks. *Perception & Psychophysics, 57*, 231–245.

Treutwein, B., & Strasburger, H. (1999). Fitting the psychometric function. *Perception & Psychophysics, 61*, 87–106.

Warabi, T., Noda, H., & Kato, T. (1986). Effect of aging on sensorimotor functions of eye and hand movements. *Experimental Neurology, 92*, 686–697.

Zelaznik, H. N., Hawkins, B., & Kisselburgh, L. (1987). The effects of movement distance and movement time on visual feedback processing in aimed hand movements. *Acta Psychologica, 65*, 181–191.

Notes

1. The optical variable tau is defined as the quotient of the optical size and the optical-size dilation rate in the case of head-on or radial approaches, and by the quotient of the relative optical-gap constriction rate that separates the moving object and the target position in tangential approaches (paths not leading to the observer; Bootsma & Oudejans, 1993; Lee, 1976; Tresilian, 1990, 1991).
2. Because the same participants took part in the CT and stop-signal experiments (making a total of 190 CT trials), the number of trials in the CT experiment (nonconstant or constant velocities) was voluntarily limited in an attempt to reduce the impact of attention requirements on performance. Note that this number of trials is commonly used in CT experiments (e.g., 10 trials per velocity condition in Haywood, 1980).
3. Absolute error (AE), which corresponds to the error regardless of its direction and provides a measure of overall task accuracy, was also calculated. This dependent variable is commonly used in CT tasks. However, we did not report it because the overall accuracy given by AE was only of minor interest here, where our specific concern was the link between acceleration and response bias.
4. The same participants performed Experiments 1 and 2 that were presented in counterbalanced order: half of the participants in each group performed the CT task followed by the stop-signal task, and the other half, the stop-signal task followed by the CT task.
5. In these statistical results, two participants were eliminated from the analysis because they were detected as outliers (i.e., extreme cases that fell outside +/- 2.5 standard deviations).

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E-mail: lobjois@inrets.fr