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RESEARCH ARTICLE

Collision avoidance behavior as a function of aging and tennis playing

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Abstract Daily living often requires pedestrians and drivers to adapt their behavior to the displacement of other objects in their environment in order to avoid collision. Yet little research has paid attention to the effect of age on the completion of such a challenging task. The purpose of this study was to examine the relationship between age and collision avoidance skill and whether a sporting activity affects this. Three age groups (20–30, 60–70, and 70–80 years) of tennis players and non-players launched a projectile toward a target in order to hit it before it was hit by another "object" (a stimulus represented by apparent motion of lights). If the participant judged that time-to-collision (TTC) of the moving stimulus was not long enough for him/her to launch the projectile in time to arrive before the stimulus, the participant had to inhibit the launching. Results showed that for the non-players the number of errors in the 70–80 year-old group was significantly higher than those of the 20–30 and 60–70 year-old groups, which did not differ from each other. However, this increase was not observed in the 70-80 year-old tennis players, demonstrating a beneficial effect of playing tennis on collision avoidance skill. Results also revealed that the older groups of both tennis players and non-players were subject to the typical age-related increase in response time. Additional analyses indicated that the 70–80 year-old non-players did not adjust their actions to these age-related changes in response time. The older tennis-playing participants, however, were more likely to adjust collision avoidance behavior to their diminished response times.

Keywords Older adults · Physical activity · Collision avoidance · Time to collision · Visuomotor calibration

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In order to avoid collisions when walking in a crowd, crossing a road, or turning left at an intersection, pedestrians and drivers have to accurately tune their actions to the displacement of other pedestrians or vehicles. This requires a visuomotor calibration (Lee et al. 1984; Simpson et al. 2003) which consists of assessing whether there is enough time, plus, usually, a safety margin, to complete an action before an opposing object arrives at a contact point (i.e., time-to-collision, TTC; Schiff and Detwiler 1979; Schiff and Oldak 1990). The task is not one of perceiving the size of the gap in absolute terms but the size of the gap in terms of time to act (Simpson et al. 2003). Although the strategies used by older adults when faced with an object in their travel path have been described recently (e.g., Gérin-Lajoie et al. 2006; Kovacs 2005), there is little work investigating how older adults perform in time-constrained collision-avoidance situations.

Oxley et al. (2005) studied the age-related differences (ages 30–45, 60–69, and over 75) in the ability to select safe TTC in a simulated street-crossing situation (projection onto a screen of two approaching vehicles). Participants were asked to decide as fast as possible (by pressing a button) whether they would or would not cross between the two vehicles. Results showed that the rate of accepted crossings increased with TTC, but that this increase was less in the older participants. For a given TTC, older participants accepted crossings less often than the 30–45 year-old group, preferring crossings that offered longer time gaps. As a second step in this study, the individual time needed to cross a road of the same width as the one used in the street-crossing situation (without displaying visual traffic scenes) was also measured. This measure was conducted to determine the rate of unsafe decision (accepted crossings for TTC inferior to the crossing time) and missed opportunities (rejected crossings for TTC superior to the crossing time). This analysis revealed that the 60–69 year-old group was quite cautious, with a large number of missed opportunities, whereas the participants over 75 were very risky with a large number of unsafe decisions.

Nevertheless, the rate of unsafe decisions in this study, together with recent results of Te Velde et al. (2005), questions the ecological validity of estimation tasks. Te Velde et al. (2005) showed that an estimation task triggered a greater number of unsafe decisions than a crossing task. At a theoretical level, this result is in line with the theory of Goodale and Milner (1992) (see also Milner and Goodale 1995) that two different visual systems would be involved depending on task constraints. The ventral stream, responsible for the processing of information necessary to identify and recognize objects or events would be involved in the estimation task. The dorsal stream, which utilizes visual information necessary for the control and guidance of motor behavior, would subserve the perception–action coupling (Tresilian 1995) and would be involved in the crossing task. As a result, an estimation task is presumed not to reliably represent visual timing behavior as it does not tap the visual system normally involved in a naturally coupled situation (see also Cavallo et al. 2006).

Moreover, the fact that in an estimation task the available time and the crossing time cannot be compared potentially affects the perception of whether the street can or cannot be crossed. Consequently, the separate assessment of gap selection and crossing time, as in the study of Oxley et al. (2005), does not allow an examination of the older adults' ability to calibrate perception and action, nor whether aging affects their ability to coordinate movement with visual information.

Considerable evidence now exists to show that training (e.g., Kramer et al. 2002), professional expertise (e.g., Bosman 1993, 1994; Salthouse 1984), or regular physical activity (e.g., Lupinacci et al. 1993) can reduce or even eliminate typical age-related declines in a number of sensorimotor and cognitive processes (Fisk and Rogers 2000). Whereas much of the current research has focused on the effects of physical activity on cognition and brain health (e.g., Churchill et al. 2002; Colcombe et al. 2003), few studies have dealt with such effects on perceptual and motor processes and the ability to tune responses to a moving object. Among the latter are included findings showing that reaction and movement times were relatively less in older participants who played regularly at ball sports (e.g., Spirduso 1975; Spirduso and Clifford 1978) or exhibited greater physical fitness (e.g., Baylor and Spirduso 1988; Etnier et al. 2003). Other studies also found that physical-activity programs positively affected older adults' ability to tune responses to the displacement of a moving object in a coincidence-timing (CT) task (Del Rey 1982; Haywood 1980) and that increased levels of physical activity were related to improved CT performance (Christensen et al. 2003). Furthermore, Lobjois et al. (2006) showed that older adults who had played tennis regularly (where CT processes are critical) yielded similar CT performance to their younger counterparts even though they faced the typical detrimental effects of age on elementary processes (increase in the visuomotor delay).

On this basis, it is arguable that physical and sport activity could have a positive influence on people's collision-avoidance ability as they become older. Two mechanisms could explain this benefit. First, such activity could maintain elementary perceptual and motor processes at an optimal level. Second, a possible decline in these processes could be better taken into account by active older adults with frequent up-dates of visuomotor calibrations. This would support the argument of Lee et al. (1984) that older adults need to regularly re-assess their movement speed in order to keep efficiency when interacting with moving objects.

Three issues were of particular interest. First, this study aimed at identifying perceptual and motor processes responsible for the age-related differences in a collision-avoidance task. The second goal was to assess whether the effects of age on collision-avoidance behavior would be mitigated in an older population that played tennis regularly. If a benefit of playing tennis was indeed found, it was presumed that the examination of these two issues would provide insight into whether the benefit was due to the maintenance of elementary processes or to better perception of action possibilities.

Method

Participants

Participants were 48 male volunteers between the ages of 20 and 30, 60 and 70, and 70 and 80 years who were selected on the basis of their history of playing tennis (tennis players or non-tennis players). Thus there were six groups of eight participants each. The 20–30 year-old groups were composed of students and the older groups of retired individuals living on their own. The non-players had no (previous or current) experience in tennis or other ball games. Tennis players were required to have played tennis between 2 and 4 h a week for at least 10 years. The mean number of years of tennis playing for the three age groups was 15, 31, and 37 years (SD = 3, 16, and 19 years), respectively. All the players were active in their tennis clubs, with a significant history of playing, but neither the younger nor the older players were of professional caliber. These criteria were chosen to recruit tennis players who played on a regular basis but were not "experts" in the game. Our goal was to study the effects of "social" playing, like that done by most older tennis players, rather than expert playing.

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

Experimental design and task

The experimental display was composed of (1) a linear runway (4 m long) with 200 light-emitting diodes (LEDs) whose successive illumination simulated the horizontal linear motion of an object from left to right, ending on a target, and (2) an aluminium boxcar (8 cm large and 20 cm long) with wheels that moved along a horizontal track (2.44 m long) perpendicular to the LED runway, ending at the same target as the simulated moving object.

Participants held the boxcar in their right hand and were asked to launch it so that it reached the target before the simulated moving object (hereinafter called simply "the moving object"). If they judged that this was not possible, they had to inhibit the launching of the boxcar. The task was designed so that the participants had to calibrate perception—arrival time of the moving object—and action—the time needed to make the boxcar arrive at the target (Lee et al. 1984; Oudejans et al. 1996; Simpson et al. 2003).

Two electric contact switches, placed under the boxcar's path, were used to detect the position and timing of the boxcar on the track. The first switch, placed on the track at the beginning of the boxcar's path, allowed the recording of movement initiation. The second switch, placed on the track at the target, was used to compute the launching time and to determine whether or not the boxcar arrived before the object.

The speed of the moving object varied between 3.94 and 1.97 m/s (i.e., 3.94, 3.502, 3.152, 2.865, 2.626, 2.424, 2.251, 2.101 and 1.97 m/s), but the viewing distance was held constant (3.94 m). Consequently, TTC varied between 1 and 2 s (i.e., 1, 1.125, 1.25, 1.375, 1.5, 1.625, 1.75, 1.875 and 2 s). These TTCs were chosen so that the minimum and maximum available times presented favorable and unfavorable situations to both the young and the old participants. The decision to launch or not to launch and the response time when a launch was made were recorded on each trial.

Experimental procedure

First, participants made practice launches of the boxcar as many times as they wanted. Then, the participants were given ten trials to launch the boxcar, with as much acceleration as possible, at the first appearance of the moving object, in order to become familiarized with the extent to which they could minimize their response time. After the experimenter's explanation, a training session consisting of 15 randomly presented trials with three different TTCs (2.63, 1.31 and 0.88 s) was held. At the beginning of each trial, a preparatory signal was given in the form of a 1-s illumination of the first LED. After each trial, feedback was given to the participants: When the boxcar arrived at the target before the moving object, the LED which corresponded to the position of the moving object at this time was relit. When the boxcar arrived after the moving object, the last LED was relit. When the participant did not launch the boxcar, no information was given to the participants.

The testing session consisted of one block of 45 trials (5 trials per TTC condition). TTC conditions were presented randomly to each participant. During the experimental session, the preparatory signal and feedback were the same as in the training session.

Data analysis

Mean selected TTC and transition threshold

The mean TTC selected by each participant—as indicated by a launch of the boxcar—was computed using a logistic regression analysis on the raw data, i.e., on the TTCs for

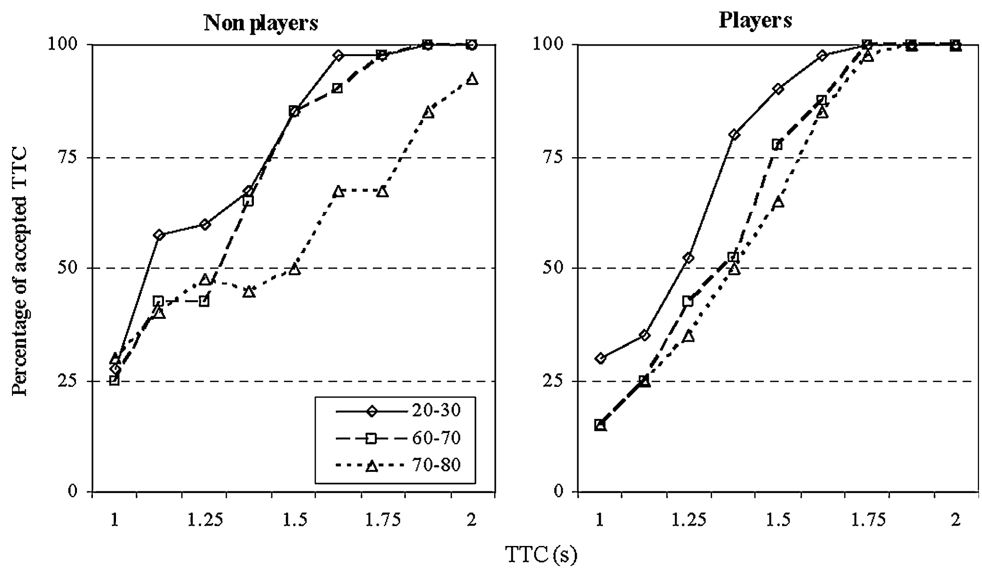

Fig. 1 Percentage of accepted TTC as a function of age, tennis playing and TTC

each launch (see Fig. 1). The following logistic function was used to determine the transition point between the decision not to launch and the decision to launch (argument α of the function which corresponds to the TTC at which participants launched 50% of the time): $F(x) = \frac{1}{1+e^{-\left(\frac{x-\alpha}{\beta}\right)}}$, where x is TTC. The transition threshold was also computed (argument β which corresponds to half the difference between the arguments for function values of 0.25 and 0.75). This threshold indicates the abruptness of the transition from rejecting to accepting TTC, and whether the perception of action possibilities is accurate. The more the behavior is finely tuned to TTC, the more this transition will be abrupt (see Oudejans et al. 1996).

Response time

Means of total response time (TT), decision time (DT) and launching time (LT) were calculated for each participant. TT was equal to the time between the appearance of the moving object and the arrival of the boxcar at the collision point. DT was equal to the time between the appearance of the moving stimulus and the response initiation. LT was equal to the time between the response initiation and the arrival of the boxcar at the collision point.

Safety margin

The safety margin corresponded to the difference between the minimum TTC (TTC_{Min}; mean of the lower quartile of individual distributions of the TTCs when launches were made, i.e., 25% of the shortest TTCs when launches were made) and the minimum TT (TT_{Min}; mean of the lower quartile of TT individual distributions, i.e., 25% of the fastest TTs). This safety margin was taken to indicate either a cautious behavior when it was large and positive or a risky behavior when it was close to zero or negative. Note that the lower quartiles for TTC and TT, instead of the mean, were selected because we considered that the safety margin was meaningful only in critical situations with a high time constraint.

Error analysis

Two different errors of decision were analyzed: the missed opportunities and the collisions. Missed opportunities corresponded to trials in which the participants did not launch but TTC was above their individual TT_{Min}. Collisions corresponded to trials in which participants launched but the boxcar arrived at the target after the moving object. Two types of collisions were distinguished. Perceptual collisions were trials in which a launch was made but the TTC was below individual TT_{Min}. In other words, participants launched but the TTC was not long enough. Motor collisions corresponded to trials in which TTC was above TT_{Min} but the boxcar arrived at the target after the moving object. In other words, participants had enough time to be successful but initiated their response and/or launched the boxcar too slowly.

All other decisions (i.e., TTC rejected when inferior to TT_{Min}, positive time interval between the effective arrival of the moving object and the boxcar on the target when a launch was made) were regarded as correct responses.

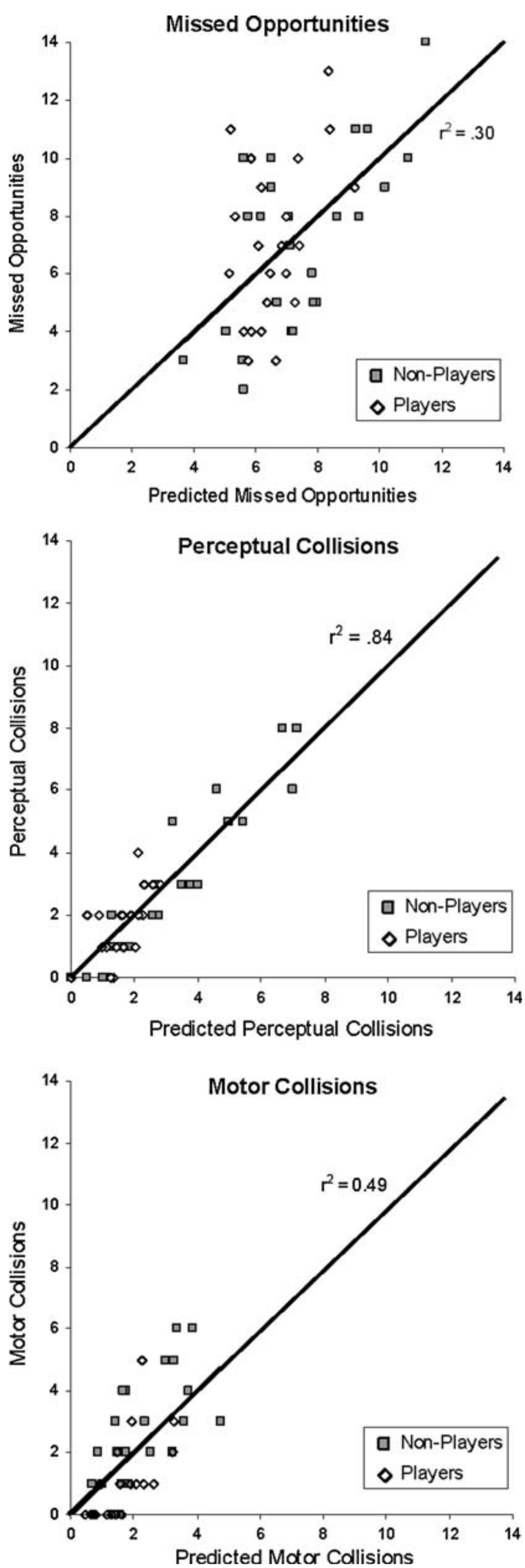

Fig. 2 Missed opportunities (*top panel*), perceptual collisions (*middle panel*) and motor collisions (*bottom panel*) as a function of predicted missed opportunities, perceptual collisions, and motor collisions, respectively, for players and non-players. Prediction of missed opportunities and perceptual collisions were obtained on the basis of a multiple regression analysis with transition threshold, safety margin, DT_{Min}, and LT_{Min} as independent variables. The multiple-regression equation for missed opportunities can be written as, missed opportunities = (11.83 × transition threshold) – (7.34 × TD_{Min}) + 7.85. The equation for perceptual collisions is, perceptual collisions = (–11.49 × safety margin) + (5.06 × transition threshold) + (2.31 × DT_{Min}) – (1.43 × LT_{Min}) + 2.37. Prediction of motor collisions was obtained on the basis of a multiple regression analysis with SD of TT, DT and LT as predictors. The regression equation for motor collisions can be written as, motor collisions = (22.58 × SD LT) + (8.70 × SD TT) – 1.77

All variables were input into analyses of variance with age (20–30, 60–70, and 70–80) and tennis playing (non-players and players) as between-participant factors. The significance level was set at 0.05 for all statistical analyses. The effect size (η^2) was also computed. Significant effects were further examined using the Newman–Keuls post-hoc test.

Results

Figure 1 plots the participants' responses as a function of age, tennis playing, and TTC. All data are reported in Table 1 for each of the six groups.

Mean selected TTC and transition threshold

The $\text{age}_3 \times \text{tennis playing}_2$ ANOVA on the mean selected TTC revealed a main effect of age, $F(2,42) = 3.47$, $P < 0.05$, $\eta^2 = 0.14$. Post hoc test showed that the mean TTC selected by the 70–80 year-olds (M = 1.34 s) was significantly longer than the one of the 20–30 year-old group (M = 1.17 s); the 60–70 year-olds did not differ from the other groups (M = 1.26 s). There were no other main effects or interactions (Table 1).

The $\text{age}_3 \times \text{tennis playing}_2$ ANOVA on the transition threshold revealed a main effect of age, $F(2,42) = 13.19$, $P < 0.0001$, $\eta^2 = 0.39$, tennis playing, $F(1,42) = 15.16$, $P < 0.001$, $\eta^2 = 0.27$, as well as an interaction between these two factors, $F(2,42) = 7.83$, $P < 0.01$, $\eta^2 = 0.27$. The 70–80 year-old group's transition threshold (M = 0.27 s) was significantly longer than that of the 20–30 (M = 0.11 s) and 60–70 year-old groups (M = 0.15 s) who did not differ from each other. The transition threshold for the non-players (M = 0.23 s) was longer than for the players (M = 0.13 s). A post hoc test on the interaction between age and tennis playing revealed that the transition threshold for the 70–80 non-players was significantly longer than the one of all other groups (Table 1).

Response time[1,2]

The $age_3 \times$ tennis $playing_2$ ANOVA on TT yielded a main effect of age, $F(2,42) = 4.75$, $P < 0.05$, $\eta^2 = 0.18$; TT for the 70–80 year-olds (M = 1.39 s) was longer than for the 20–30 year-old group (M = 1.22 s); the 60–70 year-old group did not differ from the other groups (M = 1.29 s). There were no other main effects or interactions (see Table 1).

The $age_3 \times$ tennis $playing_2$ ANOVA on DT revealed a main effect of tennis playing, $F(1,42) = 4.36$, $P < 0.05$, $\eta^2 = 0.09$; the players (M = 0.42 s) made their decisions more quickly than the non-players (M = 0.49 s). No other main effect or interaction was found (Table 1).

The $age_3 \times$ tennis $playing_2$ ANOVA on LT revealed only a main effect of age, $F(2,42) = 4.57$, $P < 0.05$, $\eta^2 = 0.18$; LT of the 70–80 year-old group (M = 0.91 s) was significantly longer than that of the 20–30 year-old group (M = 0.76 s); the 60–70 year-old group did not differ from the other groups (M = 0.85 s).

Safety margin

The $age_3 \times$ tennis $playing_2$ ANOVA on the safety margin revealed a main effect of age, $F(2,42) = 7.13$, $P < 0.01$, $\eta^2 = 0.25$; the safety margin was lower for the 70–80 year-olds (M = 0.028 s) than for the 20–30 (M = 0.149 s) and 60–70 year-olds (M = 0.109 s), who did not differ from each other. The analysis also yielded a main effect of tennis playing, $F(1,42) = 12.15$, $P < 0.01$, $\eta^2 = 0.22$; the safety margin was lower for the non-players (M = 0.049 s) than for the players (M = 0.142 s). The interaction between age and tennis playing was also significant, $F(2,42) = 3.65$, $P < 0.05$, $\eta^2 = 0.15$. Post hoc comparison showed that the safety margin for the 70–80 year-old non-player group was lower than that of the five other groups (Table 1). Moreover, this group was the only one to have a negative safety margin.

Error analysis

Missed opportunities (TTC was above TT_{Min}, allowing a safe response, but the boxcar was not launched)

The $age_3 \times$ tennis $playing_2$ ANOVA on the average number of missed opportunities revealed a main effect of age, $F(2,42) = 6.35$, $P < 0.01$, $\eta^2 = 0.23$; missed opportunities were more numerous for the 70–80 year-olds (M = 8.9) than for the 20–30 (M = 5.9) and 60–70 year-olds (M = 6.2), who did not differ from each other. There were no other main effects or interactions. Results for each age and tennis-playing group are presented in Table 1.

Perceptual collisions (boxcar was launched but TTC was below TT_{Min})

The $age_3 \times$ tennis $playing_2$ ANOVA on the average number of perceptual collisions revealed a main effect of age, $F(2,42) = 6.51$, $P < 0.01$, $\eta^2 = 0.24$, tennis playing, $F(1,42) = 8.55$, $P < 0.01$, $\eta^2 = 0.17$, as well as an interaction between these two factors, $F(2,42) = 7.23$, $P < 0.01$, $\eta^2 = 0.26$. Post hoc comparison for the age effect yielded a higher number of perceptual collisions in the 70–80 year-olds (M = 3.1) than in the 20–30 (M = 1.1) and 60–70 year-olds (M = 1.9) who did not differ from each other. Tennis players (M = 1.3) made significantly fewer perceptual collisions than non-players (M = 2.7). A post hoc test for the age and tennis playing interaction showed that 70–80 year-old non-player group made more perceptual collisions than all other groups (Table 1).

[1] Standard deviations (SD) of TT, DT and LT were also calculated and submitted to an $age_3 \times$ tennis $playing_2$ ANOVA. The analysis on SD TT yielded no significant effect or interaction. The analysis on SD DT yielded a main effect of age, $F(2,42) = 4.31$, $P < 0.05$, $\eta^2 = 0.17$, and tennis playing, $F(1,42) = 10.18$, $P < 0.01$, $\eta^2 = 0.20$, and an interaction between these two factors, $F(2,42) = 3.91$, $P < 0.05$, $\eta^2 = 0.16$. A post hoc test on this interaction yielded significant differences between the 70–80 year-old non-player group and the other groups. The analysis on SD LT yielded a main effect of age, $F(2,42) = 8.71$, $P < 0.001$, $\eta^2 = 0.29$, due to a more variable LT for the 70–80 year-olds than for the other two groups, as well as a main effect of tennis playing, $F(1,42) = 9.83$, $P < 0.01$, $\eta^2 = 0.19$, the non-players having a more variable LT than the players. SDs are given for each group in Table 1.

[2] To examine participants' abilities to adjust behavior to the available time, the relationships between response times (TT, DT and LT) and TTC were assessed. To this end, the individual linear relationships of individual TT, DT and LT as a function of TTC were calculated for each participant separately. Fisher *Z*-transformations of the correlation coefficients (*r*), slopes, and intercepts of the individual linear regressions were analysed. Analyses of the TT/TTC relationships revealed age differences on Fisher *Z*-scores, $F(2,42) = 4.87$, $P < 0.05$, $\eta^2 = 0.19$, which were higher for the young group than for the older groups, and on the intercept, $F(2,42) = 9.04$, $P < 0.001$, $\eta^2 = 0.30$; which was lower for the young group than for the older groups. Analyses of the DT/TTC relationships did not reveal significant effects or interactions. Analyses of the LT/TTC relationships yielded age differences on the *Z*-scores, $F(2,42) = 3.52$, $P < 0.05$, $\eta^2 = 0.14$, which were higher for the young group than for the older groups, and on the intercept, $F(2,42) = 5.31$, $P < 0.01$, $\eta^2 = 0.20$, which was higher for the 70–80 year-olds than for the both other groups. The low slopes and *Z* scores of the relationship between TTC and response times, and the lack of differences between ages or tennis-playing groups suggests that the behavioral adjustment to TTC was minimal, indicating that the participants, whatever their age and tennis-playing group, were likely to use a constant response-time strategy to perform the task (Table 1).

Table 1 Means as a function of age and tennis playing for each computed variable

		20–30 years		60–70 years		70–80 years	
		Non-players	Players	Non-players	Players	Non-players	Players
Mean accepted TTC (s)		1.161	1.185	1.217	1.309	1.326	1.352
Threshold (s)		0.114	0.116	0.183	0.118	0.393	0.150
TT (s)	M	1.230	1.216	1.308	1.280	1.464	1.334
	SD	0.124	0.115	0.122	0.115	0.175	0.115
DT (s)	M	0.463	0.452	0.478	0.408	0.540	0.426
	SD	0.085	0.088	0.105	0.066	0.165	0.084
TL (s)	M	0.767	0.764	0.830	0.878	0.924	0.908
	SD	0.107	0.084	0.106	0.080	0.159	0.116
Response adaptation to TTC							
TT	*r* (*Z*-score)	0.41 (0.48)	0.51 (0.59)	0.28 (0.30)	0.22 (0.24)	0.31 (0.34)	0.16 (0.17)
	Slope	0.205	0.215	0.127	0.116	0.176	0.060
	Intercept	0.897	0.869	1.102	1.087	1.183	1.234
DT	*r* (*Z*-score)	0.39 (0.42)	0.39 (0.43)	0.19 (0.19)	0.14 (0.14)	0.21 (0.23)	0.30 (0.31)
	Slope	0.142	0.119	0.062	0.047	0.118	0.124
	Intercept	0.230	0.261	0.379	0.327	0.345	0.216
TL	*r* (*Z*-score)	0.21 (0.24)	0.27 (0.29)	0.16 (0.16)	0.15 (0.16)	0.10 (0.11)	–0.11 (–0.12)
	Slope	0.063	0.096	0.066	0.067	0.057	–0.064
	Intercept	0.667	0.608	0.723	0.763	0.837	1.018
TT^{a}_{Min} (s)		1.092	1.085	1.167	1.183	1.273	1.191
DT^{b}_{Min} (s)		0.405	0.389	0.408	0.372	0.460	0.372
LT^{c}_{Min} (s)		0.688	0.696	0.760	0.811	0.812	0.819
TTC_{Min} (s)		1.230	1.244	1.243	1.325	1.205	1.314
Safety margin (s)		0.138	0.159	0.076	0.142	–0.068	0.123
Missed opportunities	*N*	44	50	49	51	79	64
	Mean	5.50	6.25	6.13	6.38	9.88	8.00
Perceptual collisions	*N*	5	12	21	9	39	11
	Mean	0.63	1.50	2.63	1.13	4.88	1.38
Motor collisions	*N*	16	2	17	4	31	16
	Mean	2.00	0.25	2.13	0.50	3.88	2.00

[a] The $age_3 \times$ tennis $playing_2$ ANOVA revealed a main effect of age, $F(2,42) = 4.3$, $P < 0.05$, $\eta^2 = 0.17$, with a significant difference between the 20–30 and 70–80 year-old adults

[b] The $age_3 \times$ tennis $playing_2$ ANOVA yielded no significant effects or interactions

[c] The $age_3 \times$ tennis $playing_2$ ANOVA revealed a main effect of age, $F(2,42) = 3.96$, $P < 0.05$, $\eta^2 = 0.16$, with a significant difference between the 20–30 year-olds and both older groups

Motor collisions (TTC was above TT_{Min} and the boxcar was launched but arrived at the target after the moving object)

The $age_3 \times$ tennis $playing_2$ ANOVA on the average number of motor collisions revealed a main effect of age, $F(2,42) = 8.87$, $P < 0.001$, $\eta^2 = 0.30$, as well as a main effect of tennis playing, $F(1,42) = 20.51$, $P < 0.0001$, $\eta^2 = 0.33$. A post hoc test for the age effect yielded a significantly higher number of motor collisions in the 70–80 year-old group (M = 2.9) in comparison with the other two groups which did not differ from each other (M = 1.1 and 1.3 for the 20–30 and 60–70 year-old groups, respectively). Tennis players (M = 0.9) made significantly fewer motor collisions than non-players (M = 2.7). Results for each age and tennis-playing group are presented for information in Table 1.

Error origin

Finally, in order to explain the origin of the errors, forward stepwise multiple regression analyses were used with each error as the dependent variables and several variables presented above as predictors. Missed opportunities and perceptual collisions can be considered as perceptual errors due to a failure in the estimation of TTC or in the estimation of the time required for action. Five variables were used as predictors:

1. Transition threshold: this variable can be considered as an indicator of the efficiency of the perceptual processes; the shorter the transition threshold, the more accurate the perceptual processes and the smaller the number of missed opportunities and perceptual collisions.
2. Safety margin: on the one hand, a negative or short safety margin may be associated with a high number of perceptual collisions but with few missed opportunities; on the other hand, a large safety margin may be associated with few perceptual collisions but with a high number of missed opportunities.
3. TT_{Min}, DT_{Min} and LT_{Min}: on the one hand, an increase in one of these variables which reflected response time could induce an increase in the number of missed opportunities by an inappropriate increase in the safety margin (i.e., overcautious behavior); on the other hand, such an increase could also induce an increase in the number of perceptual collisions in participants who had difficulty taking into account an increase in the response time.

Missed opportunities

In the first step of the stepwise regression, the transition threshold entered the equation with a significant correlation of –0.49 [$F(1,46) = 14.81$, $P < 0.001$], which explained 24% of the total variance. In the second and last step, DT_{Min} entered the equation but its effect was not significant [$t(45) = -1.93$, $P = 0.058$]. The transition threshold ($\beta = 0.53$) and DT_{Min} ($\beta = -0.24$) explained 30% of the total variance with a significant correlation of 0.55 [$F(2,45) = 9.73$, $P < 0.001$]. The equation of the multiple regression analysis is depicted in Fig. 2 (top panel). Even if the transition threshold explains a significant part of the number of missed opportunities, the weak value of r^2 prevents any strong conclusion about this relationship. It should be pointed out that this result could be due to age and tennis experience having a weak effect on missed opportunities. Both results probably mean that this kind of error is not relevant to the factors we manipulated in this experiment.

Perceptual collisions

In the first step of the stepwise regression, the safety margin was the best predictor of perceptual collisions with a significant correlation of –0.88 [$F(1,46) = 152.49$, $P < 0.0001$], which explained 77% of the total variance. In the second step, the transition threshold entered the equation. The safety margin ($\beta = -0.62$) and transition threshold ($\beta = 0.34$) explained 82% of the total variance with a significant correlation of 0.90 [$F(2,45) = 100.42$, $P < 0.0001$]. In the third and fourth step, DT_{Min} and LT_{Min} entered the equation but their respective effect was not significant [$t(44) = 1.37$, $P = 0.17$ for DT_{Min}; $t(43) = -1.04$, $P = 0.29$ for LT_{Min}]. The safety margin ($\beta = -0.64$), transition threshold ($\beta = 0.32$), DT_{Min} ($\beta = 0.11$), and LT_{Min} ($\beta = -0.09$) explained 84% of the total variance with a significant correlation of 0.92 [$F(4,43) = 57.01$, $P < 0.0001$]. The equation of the multiple regression analysis is depicted in Fig. 2 (middle panel).

This analysis indicates that participants with a lower safety margin were also those who had a higher number of perceptual collisions. As safety margin was assumed to correspond to ability to integrate changes in the response times, a regression analysis was undertaken with DT_{Min} and LT_{Min} as predictors of safety margin, and LT_{Min} first to enter the equation. There was a significant correlation of 0.44 between safety margin and LT_{Min} [$r^2 = 0.20$, $F(1,46) = 11.17$, $P < 0.01$], followed by DT_{Min}. LT_{Min} ($\beta = -0.55$) and DT_{Min} ($\beta = -0.47$) explained 40% of the total variance with a significant correlation of 0.63 [$F(2,45) = 14.97$, $P < 0.0001$]. This analysis actually indicated that the longer the LT_{Min} and DT_{Min}, the shorter the safety margin.

Motor collisions

Motor collisions corresponded to launchings that occurred when TTC was greater than TT_{Min}, but the boxcar arrived at the target after the moving object. For these trials, the decision to launch was correct but the launching itself took too long. Thus, motor collisions could be due to difficulty in managing response times that are attuned to available time. In a previous analysis, we showed that participants mainly operated in a constant-time mode regardless of TTC, with a slight decrease in response time for some participants for the shortest TTC. Thus, participants who had the most variable response times could also be those who had the larger number of motor collisions. Motor collisions would be due to an unexpected delay in the completion of the response in some trials. This hypothesis was tested using a forward stepwise regression analysis, with motor collisions as the dependant variable and SD of TT, DT and LT as independent variables.

In the first step of the stepwise regression, SD LT entered the equation with a significant correlation of 0.67 [$F(1,46) = 36.78$, $P < 0.0001$], which explained 44% of the total variance. In the second and last step, SD TT entered the equation but its effect was not significant [$t(45) = 1.89$, $P = 0.065$]. SD LT ($\beta = 0.54$) and SD TT ($\beta = 0.24$) explained 49% of the total variance with a significant correlation of 0.70 [$F(2,45) = 21.19$, $P < 0.0001$]. The equation of the multiple regression analysis is depicted in Fig. 2 (bottom panel). This analysis showed that the variability in LT was a good predictor of motor collisions.

Discussion

The goal of this study was twofold. First, it was designed to examine differences between younger and older adults in a collision avoidance task. Second, it was designed to test the effects of tennis playing on collision avoidance behavior with advancing age, with the hypothesis that a regular sporting activity, such as tennis, in which perceptual and motor processes are critical, could help older tennis players avoid collisions more easily than their non-player counterparts.

The results showed that older adults who had no specific physical activity made many more errors of each type than the 20–30 year-olds, confirming that collision avoidance situations are increasingly difficult with advancing age. This was particularly true in the group of the oldest participants who had an increase in the number of errors in comparison with their younger counterparts, a finding previously shown by Oxley et al. (2005) in a simulated gap selection task. It was found here that tennis playing was associated in older adults with a reduction, relative to their non-playing peers, in perceptual and motor collisions but not in missed opportunities.

Perceptual errors (missed opportunities and perceptual collisions) were supposed to be linked to the size of the safety margin and/or to the extent of the transition threshold. Results for the missed opportunities were not very conclusive. One could have expected that elderly participants missed TTCs appropriate for launching because of a less accurate perception of the available time or an exaggerated safety margin connected to an exaggerated perception of their action capacity. However, the effect of age on missed opportunities was not very strong (Table 1). For this reason, it was not possible to show a relevant relationship between these errors and the perceptual variables registered. On this basis, it can be concluded that missed opportunities were not really an aging issue in the task we used in this study.

Findings for the perceptual collisions were conclusive. The age and tennis playing interaction revealed that the 70–80 year-old non-players made many more errors than their tennis player counterparts and both groups of 20–30 year olds. To explain the possible origin of these errors, it was hypothesized that this could come from a less accurate perception of TTC and/or of the time required for action. Results of the regression analysis supported both hypotheses. Participants who had the largest transition threshold and the shortest safety margin were also those who had the most perceptual collisions.

According to Oudejans et al. (1996), an increase in the transition threshold indicates that avoidance behavior is less finely tuned to available time. The age-related increase observed in the transition threshold suggests then that perception of affordances (Gibson 1979; Warren 1984) is affected with advancing age and that older adults are faced with a less accurate perception of action possibilities. Following the results of Hancock and Manser (1997) or DeLucia et al. (2003), this finding furthermore suggests that TTC estimation is also affected with aging.

Although the mean accepted TTC increased with age, suggesting that older adults were able to take into account their changing sensory and motor abilities when making a decision (see Lobjois and Cavallo 2007; Oxley et al. 2005, for a similar result), this increase does not seem long enough to conclude that this is the case. Results showed that the 70–80 year-old non-players had a negative safety margin and that this safety margin was significantly related to an increase in the launching time. This finding, combined with their higher number of perceptual collisions, suggests that the 70–80 year-olds were not able to accurately integrate their diminishing perceptual/motor abilities in the safety margin, leading to them accept TTCs that were too short. This interpretation is supported by previous research examining the relationship between age-related decrements and the lack of behavioral adaptations in older drivers and pedestrians (e.g., Holland and Rabbitt 1992). It is also in line with the assertion of Lee et al. (1984) that older adults need to regularly re-assess movement speed in order to establish visuomotor calibration.

Taken together, these results furthermore suggest that older adults are less efficient at perceiving an affordable gap when spatiotemporal relations are of importance. As affordance of a gap depends on the distance to cover, the time available, and the time needed to cover this distance (Lee et al. 1984), both overestimation of gap size and underestimation of crossing time can contribute to errors (Plumert et al. 2004). Consequently, the age-related effect on the number of perceptual collisions suggests that part of the older adults' inefficiency could come from an overestimation of their action capabilities.

Finally, the finding that age affects the size of the safety margin and the number of perceptual collisions does not match the proposal that elderly most likely need greater safety margins than younger adults in order to compensate for their diminished ability to manage perilous situations (see Harrell 1991; Harruff et al. 1998; Lobjois and Cavallo 2007, concerning aging and street crossing; see also Gérin-Lajoie et al. 2006, who showed that older adults increased the protective zone around the body when they had to circumvent obstacles during walking). Based on the recent results of Andersen and Enriquez (2006), who reported that older adults' sensitivity to detect possible collisions decreased with the viewing time of the visual scene, or those of Oxley et al. (2005), who showed a similar pattern of results on the ability to select safe crossing gaps, the age-related effect on the safety margin suggests that older adults are even more affected when time constraints are high, such as in the current study.

As expected, tennis-playing experience was associated with a reduction in the number of perceptual collisions. This effect was linked to a greater ability to keep short the transition threshold and to keep long the safety margin. This suggests that the launching behavior of the group of older tennis players was much more finely tuned to TTC than was that of their non-player counterparts (Oudejans et al. 1996) and that the former are more likely to distinguish favorable and unfavorable situations. The older players were also able to keep a longer safety margin than the older non-players. This result was not due to this group maintaining the same motor capabilities as the younger participants, since response time (LT and TT) increased with age and tennis playing (see Spirduso and Clifford 1978, for a similar result concerning the effect of tennis playing on movement time). Although their response time increased, older players integrated this increase correctly to make appropriate judgments. Finally, it can reasonably be proposed that their better knowledge of action capabilities comes from frequent up-dates of visuomotor calibrations.

Results for the motor collisions revealed that age and tennis playing affected the number of motor collisions but did not interact. The number of motor collisions increased with age but this was significantly less so in older tennis players. Furthermore, regression analysis showed that motor collisions depended on the participants' ability to minimize launching time variability from trial to trial. As participants mainly operated in a constant-time mode regardless of TTC in the task, those who had less stable control of their launching time over trials were also those who had more numerous motor collisions.

These findings were consistent with the main effects of age and tennis playing on the launching-time variability. Relative to the other groups, the 70–80 year-old group made significantly more motor-collision errors due to their significantly more inconsistent launching-time. On the other hand, although all older participants were liable to commit more motor-collision error than the 20–30 year olds, tennis playing was associated with inhibiting an age-related increase in SD LT (see Spirduso and Clifford 1978, for a similar result) and with a reduction in the number of motor collisions.

Once again, a larger safety margin would probably have favored avoidance of these collisions as the participants would have compensated correspondingly for launching time changes from trial to trial. As task constraints did not allow participants ongoing control of the boxcar displacement because of the impulse-type response, it would be useful to test older adults in an interactive situation to study how they manage on-line control, and whether they remain able to cope with ongoing changes in the situation (e.g., acceleration of approaching objects, misperception of the available time). Finally, it can be supposed that, in addition to altering the ability to complete action duration appropriate to TTCs, launching time inconsistency could also affect older adults' ability to calibrate perception and action.

Although the results suggest that differences between older players and non-players come from participation in tennis over a substantial portion of the adult lifespan, results of cross-sectional studies must be interpreted cautiously given the potential for alternative interpretations. Positive associations between age, physical activity and superior performance do not provide information on the direction of the causality (Dustman et al. 1994; Etnier et al. 1997; Kramer et al. 2004). Therefore, one cannot rule out the possibility that the differences between the players and non-players may be the result of a self-selection bias (see also the selective attrition hypothesis of Charness and Bosman (1990), and Clarkson-Smith and Hartley (1990). According to this hypothesis, the age-related declines in some abilities may lead some people to stop their participation in sporting activities. As a result, those who continue would simply be those who do not experience classic age-related changes in relevant abilities. Tennis participation would then not compensate for declines but rather act to select only for people who have a predisposition toward fast and accurate responses, the older player groups being simply a select subset in their age cohort. Whereas this hypothesis is not testable in a cross-sectional design, the lack, in our study, of exercise-related differences on response times is inconsistent with the selection-bias hypothesis.

Moreover, many studies have also reported that higher levels of aerobic fitness can be achieved through regular participation in physical activity and are associated with gains in aspects of cognition (e.g., Emery et al. 1995; Rikli and Edwards 1991; Shay and Roth 1992; for a meta-analysis, see Colcombe and Kramer 2003). Thus, it is possible that the effects of tennis participation are confounded with the effect of overall activity and an accompanying increase in physical fitness due to tennis participation. Although this suggests that tennis/no-tennis differences might not be specific to the nature of tennis as a lifelong sporting activity, there is data on simple and choice reaction times that shows that old racquet players outperformed old men who participated in other (aerobic) activities (Spirduso and Clifford 1978) or on CT accuracy (Lobjois et al. 2006).

In conclusion, this study showed that participants over 70 years of age selected a mean TTC longer than their younger counterparts, indicating some attempt at compensating for their increased response times. However, they were also more likely to make erroneous decisions. These findings suggest that the scaling of TTC in relation to action capacities is affected with aging, which itself does correspond to more cautious behavior. This study also showed clear positive effects of tennis playing on collision avoidance abilities, an encouraging result for people who want to improve them—or at least arrest their decay. Response times were slightly better in older players than non-players, but most importantly, the older players compensated better for age-related declines and maintained a more finely tuned behavior to TTC. With regular involvement in sport activity, older tennis players continually re-assess the scaling between what the environment offers and what they can do in it. This supports the argument of Lee et al. (1984) that older adults have to regularly re-assess movement speed in order to keep efficiency when interacting with moving objects. Much work lies ahead to establish the particular benefits of experience in particular physical activities, but clearly a physically active lifestyle should be encouraged among the adult population.

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