

# Impact of Physical Activity on Executive Functions in Aging: A Selective Effect on Inhibition Among Old Adults

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The purposes of this study were to determine the impact of physical activity on three different executive functions (shifting, inhibition, and updating) and to examine whether cardiovascular fitness was a good mediator of the positive link(s) between these variables. Sixty-three young adults (18–28 years), 30 young-old adults (60–70 years) and 30 old adults (71–81 years) were divided into physically active and sedentary groups according to physical activity level (assessed from an accelerometer and the Historical Leisure Activity Questionnaire). Cardiovascular fitness was assessed by VO<sub>2</sub>max from the Rockport 1 mile. Each executive function was assessed through three different experimental tasks. ANCOVAs revealed that the effect of physical activity level was specific to the old adults and significant for inhibition, but not for updating and shifting. Mediation analysis showed that this positive effect in the old adults group was mediated by cardiovascular fitness level. The present findings highlight the positive linkages among physical activity, cardiovascular fitness, and inhibition in aging.

**Keywords:** exercise, cardiovascular fitness, cognitive performance

Cerebral and cognitive declines represent the major cause of autonomy loss in the aged population. Executive control is strongly altered during cognitive aging (Verhaeghen & Cerella, 2002), but some evidence has suggested that physical activity, aimed at improving cardiovascular fitness, is beneficial for cognitive performance in older adults, particularly in tasks tapping executive control (e.g., Colcombe et al., 2004 ; Kramer et al., 1999). However, other evidence has failed to clearly demonstrate the direct link between cardiovascular fitness and cognitive performance (Smiley-Oyen, Lowry, Francois, Kohut, & Ekkekakis, 2008; Etnier, Nowell, Landers, & Sibley 2006). Actually, the links between physical activity, cardiovascular fitness, and executive control seem to be more complex. Methodological as well as theoretical limitations may have prevented a clear demonstration

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of these links. According to Etnier and Chang (2009), researchers in this area have to more finely measure the “executive construct” by taking into account recent advances in the study of executive control.

## **Executive Functions, Physical Activity, and Aging**

Executive control can be conceptualized as a set of processes that enables us to plan, coordinate, sequence, and monitor cognitive operations (Stuss, 1992). Miyake et al. (2000) distinguished between three latent variables underlying executive control: shifting, inhibition, and updating of working memory. Shifting represents the ability to shift cognitive control between different tasks. Inhibition implies the capacity to suppress irrelevant information or prepotent responses. Updating refers to the ability to substitute old information with new information in working memory. This three-function construct has been frequently postulated in the literature and replicated in older populations, with the confirmation that aging significantly altered all three of these executive function components (Albinet, Boucard, Bouquet, & Audiffren, 2012; Fisk & Sharp, 2004; Vaughan & Giovanello, 2010). Because it is impossible to find a “pure” task assessing an executive function, multiple measures should be used to rule out this problem of “task impurity” (i.e., a single dependent variable of a given executive function can rarely be viewed as a pure measure of that executive function) (Miyake et al., 2000).

An interventional study (Kramer et al., 1999), and a subsequent meta-analysis (Colcombe & Kramer, 2003), demonstrated that long-term physical activity was more beneficial on tasks that require executive control than on tasks that do not. However, two more recent meta-analyses do not support this pattern of findings of a selective or greater benefit to this cognitive outcome (Angevaren et al., 2008; Smith et al., 2010). Moreover, some experimental studies even failed to demonstrate physical activity–related improvements on some tasks involving executive control (e.g., Smiley-Oyen et al., 2008). The heterogeneity in the tasks used across studies to evaluate executive control without a clear theoretical framework and the manifold nature of this construct may have contributed to this discrepancy. As it is difficult to compare the results from different studies, it is an important issue to clarify whether executive functions are equally modulated by physical activity level or whether physical activity targets specific executive processes within the same sample of young and older adults. One could expect that the influence of physical activity may be diverse among all the executive functions because they are sustained by extended and distinct cortical regions (Collette, Hogge, Salmon, & Van Der Linden, 2006).

Besides, another important issue that remains unsolved is to what extent a demographic moderator such as chronological age is important in the relationship between physical activity and each of the three executive functions (see Miller et al., 2012). According to the moderator model proposed by Stones and Kozma (1988), the benefits of physical activity on cognitive performance should increase with increasing age. However, inconsistent results have been reported in the literature. Some argue that the positive impact of physical activity is stronger in the early 60’s (Bunce & Murden, 2006), whereas others have shown that it is more important between 66 and 70 years (Colcombe & Kramer, 2003) or after 70 years (Renaud, Bherer, & Maquestiaux, 2010). To examine more precisely these questions in the

current study, we subdivided the older participants into a young-old group (60–70 years) and an old group (71–81 years).

## **Cardiovascular Fitness as a Mediator of Physical Activity Effects**

The positive relationship between physical activity level, cardiovascular fitness, and cognition is still under debate. The improvements in cardiovascular fitness induced by regular physical activity are thought to be associated with changes in underlying neurophysiological mechanisms, such as cerebral structure (Colcombe et al., 2003, 2006; Voelcker-Rehage, Godde, & Staudinger, 2011), cerebrovascular conductance (Brown et al., 2010), or brain-derived neurotrophic factor concentration (Erickson et al., 2011), which in turn influence cognitive performance.

Interestingly, Kramer et al. (1999) demonstrated a significant relationship between cardiovascular fitness improvements (indexed by  $\text{VO}_2\text{max}$ ), over the course of a 6-month physical activity program, and improved executive functioning among older adults. Thus, the effect of physical activity on executive functions among older adults could depend on the improvements in cardiovascular fitness. This so-called executive control/cardiovascular fitness hypothesis (Kramer et al., 1999) recently gained support from neuroimaging studies. Higher level or improvements of cardiovascular fitness were found to be related to larger cerebral volumes (Colcombe et al., 2003; 2006) and to changes in patterns of cortical recruitment in some prefrontal and parietal areas (Colcombe et al., 2004). Importantly, these structural and functional improvements were concomitant with a better cognitive performance in the corresponding executive task components. Moderate-to-vigorous physical activity would induce improvement in cardiovascular fitness, which in turn results in a better central nervous system functioning within prefrontal cortices, thereby increasing cognitive performance in executive tasks. However, some studies failed to detect the dose–response relationship between cardiovascular fitness and executive functions performance in aging (see Angevaren et al., 2008; Etnier et al., 2006; Smiley-Oyen et al., 2008). For example, Etnier et al. (2006) showed in their meta-regression analysis, that there is no significant relationship between absolute cardiovascular fitness level and cognitive performance level, or even that the relationship between gains in  $\text{VO}_2\text{max}$  and gains in cognitive performance is negative in the elderly. Smiley-Oyen et al. (2008) showed in their interventional study that, although cardiovascular fitness training can improve some executive performance in older adults, this improvement was not mediated by improvements in  $\text{VO}_2\text{max}$ .

It is difficult to draw a final conclusion on the putative mediating role of cardiovascular fitness on cognitive performance because of several flaws in the definition and operationalization of executive functions, but also of physical activity and cardiovascular fitness as developed below, rendering the comparison of all the studies very difficult. Firstly, the differences between physical activity and cardiovascular fitness have been mostly overlooked and even sometimes confused. Postulating that cardiovascular fitness might reflect physical activity level, many authors have used cardiovascular fitness level as the independent variable to distinguish groups that are expected to exhibit differences in cognitive performance (e.g., Bunce & Murden, 2006). We think, however, that it is important to distinguish physical activity and cardiovascular fitness because, albeit strongly related, they reflect

two different continuums (i.e., behavioral and physiological). Physical activity level and cardiovascular fitness can be highly correlated when the physical activity level corresponds to a stable long-standing behavior, but weakly or moderately correlated when the physical activity level corresponds to unstable or short bouts of exercise. The second issue concerns the valid assessment of physical activity. Most cross-sectional studies have only used self-reported measures (e.g., questionnaires, diaries) to assess physical activity (see Miller et al., 2012). However, given its multidimensional nature (Dishman, 2006), it is essential to use multiple parameters to obtain a good estimate of physical activity. Furthermore, some degree of objective verification is required to corroborate self-reported physical activity. An accelerometer is an interesting tool, providing minute-by-minute amounts of physical activity in a given epoch, the intensity of which can be categorized as light, moderate, and vigorous (Freedson, Melanson, & Sirard, 1998). In the current study, we thus assessed physical activity level through both objective measures obtained via an accelerometer and self-reported measures obtained by questionnaire.

## The Present Study

To date, no study has directly examined whether physical activity differentially or homogeneously impacts the different executive functions, using a well-defined theoretically driven methodological framework with multiple executive measures. In the current study, we used the three executive function factorial structure identified by Miyake et al. (2000) to examine this question, with three different tasks for each of the three identified executive functions: shifting, inhibition, and updating of working memory (see Albinet et al., 2012, for a similar approach). From three different measures tapping each specific component, we computed a composite score reflecting more selectively the postulated component than each measure alone. The aims of this study were (1a) to examine to what extent physical activity influences each executive function, (1b) to determine whether this effect varies according to an age gradient, and (2) to explore the potential mediating role of cardiovascular fitness in this relationship between physical activity and executive performance.

## Method

### Participants

Sixty-three young adults (18–28 years), 30 young-old adults (60–70 years), and 30 old adults (71–81 years), free of neurological and cardiovascular disease, participated in this study (see Table 1 for their characteristics). The older participants were recruited from senior community centers, civic groups, fitness centers, and via the use of flyers and newspaper advertisements in a medium-size town (120,000 inhabitants) in France. All the older participants were screened by their personal physician who rated them as in good health and signed a medical certificate of no contraindication to the cardiovascular fitness testing. The young adults were recruited from a pool of mature students from the University of Poitiers. Inclusion criteria were (a) being aged between 18 and 30 or between 60 and 81 years; (b) having adequate mental status (MMSE > 26) (Hébert, Bravo & Girouard, 1992); (c) leading a sedentary or active lifestyle, assessed by a validated physical activity

**Table 1 Characteristics of the Participants**

|  | Young Adults |             | Young-Old Adults |             | Old Adults  |             |
|--|--------------|-------------|------------------|-------------|-------------|-------------|
|  | Active       | Sedentary   | Active           | Sedentary   | Active      | Sedentary   |
| Age (years) <sup>a</sup>                       | 21.9 ± 1.9   | 22.0 ± 2.7  | 66.3 ± 3.0       | 66.3 ± 3.3  | 73.4 ± 2.4  | 75.4 ± 3.4  |
| Sex (M/F)                                      | 15/17        | 15/16       | 7/8              | 7/8         | 7/8         | 7/8         |
| PA score (z-score) <sup>a,b,c</sup>            | 0.9 ± 0.6    | -0.3 ± 0.3  | 0.3 ± 0.7        | -0.7 ± 0.1  | -0.2 ± 0.5  | -0.8 ± 0.2  |
| Past PA (MET-hr/wk) <sup>a,b,c</sup>           | 52.2 ± 22.2  | 12.7 ± 13.1 | 16.3 ± 12.7      | 7.2 ± 5.9   | 17.4 ± 5.3  | 5.8 ± 7     |
| Present PA (MVPA) <sup>a,b</sup>               | 43.7 ± 35.4  | 18.5 ± 17.5 | 51.1 ± 26.6      | 3.1 ± 4     | 20.4 ± 20   | 2.1 ± 4.3   |
| VO <sub>2</sub> max (mL/min/kg) <sup>a,b</sup> | 48.4 ± 6.4   | 44.2 ± 6.5  | 31.9 ± 5.1       | 23.1 ± 7.2  | 24.8 ± 6.5  | 19.7 ± 8.2  |
| BMI (kg/m <sup>2</sup> ) <sup>a,b,c</sup>      | 22 ± 2.7     | 22.7 ± 3.7  | 23.1 ± 2.2       | 27.8 ± 6.1  | 24.7 ± 3.0  | 25.8 ± 3.1  |
| Education (years) <sup>a,b</sup>               | 14.6 ± 1.5   | 14.2 ± 1.8  | 15.3 ± 3         | 13 ± 3      | 13.1 ± 4.2  | 11.7 ± 5.5  |
| Mill-Hill score (/44) <sup>a</sup>             | 33.2 ± 2.5   | 34.4 ± 4.1  | 38.9 ± 3.5       | 38.3 ± 5.4  | 38.9 ± 4.1  | 37.4 ± 4.8  |
| DSST (number) <sup>a</sup>                     | 90.3 ± 13.5  | 91.6 ± 12.8 | 63.1 ± 10.4      | 60.4 ± 12.7 | 60.7 ± 14.2 | 60.7 ± 11.4 |
| MMSE (/30)                                     | —            | —           | 29.1 ± 0.8       | 29.1 ± 1    | 29.2 ± 0.8  | 28.9 ± 1    |

*Note:* Values are means ± SD. MVPA = time in moderate-to-vigorous physical activity (min/day); DSST = Digit Symbol Substitution Test; MMSE = Mini-Mental State Examination.

<sup>a</sup>Main effect of age.

<sup>b</sup>Main effect of physical activity (PA) level.

<sup>c</sup>Age by physical activity level interaction.

questionnaire; and (d) score under the 11-point cutoff of the Geriatric Depression Scale (Bourque, Blanchard, & Vézina, 1990). Exclusion criteria were (a) using medication that could affect cardiovascular health or cognitive functions, (b) cardiovascular or neurological disease, and (c) major surgery 1 year before the testing. All participants gave written informed consent, and the study was approved by the local ethics committee. Each participant received €30 for their participation.

## Physical Activity Evaluation

Physical activity level was assessed by past life physical activity and present physical activity, so that all active participants would be characterized by a stable pattern of physical exercise over the life.

**Past Life Physical Activity.** The Historical Leisure Activity Questionnaire (HLAQ) (Kriska, Sandler, Cauley, Hom, & Pambianco, 1988) is a validated questionnaire used to assess the history of physical activity weighted by their relative intensity. In this questionnaire, participants had to report the frequency, type, intensity, and hours of physical activity performed during four age periods: 12–18 years, 19–34 years, 35–49 years, and 50 years old and more. Through the classification of physical activity intensities (established by Ainsworth et al., 2000), all activities were coded and given the specific metabolic equivalent (MET). First, average participation for each activity performed in an age period was estimated in hours per week (see the formula developed by Kriska et al., 1988). Second, hours/week for each activity was multiplied by the corresponding activity's MET. Third, the MET-hours/week values for each activity were summed within an age period. The dependent variable was the total MET-hours/week performed in leisure physical activity averaged across all age periods.

**Present Physical Activity.** Present physical activity was measured by the Actigraph Model GT1M. This small uniaxial piezoelectric accelerometer was worn superior to the iliac crest. Participants were briefed to wear the Actigraph for 2 days within a week: one day that they considered as “the most physically active” and another day that they considered as “the most physically inactive” for a typical week. They were instructed to remove it for sleeping and bathing only, and to complete a log to recall when the Actigraph was worn. Subsequently, data were downloaded using the manufacturer's software and activity counts were delineated in intensity categories using the Freedson et al. (1998) equation. As many guidelines recommend that physical activity needs to be performed at least at moderate intensity to achieve health benefits among older adults and that moderate intensity physical activity was recently described as 4.0–5.9 METs (see Thompson et al., 2009), we assessed for each participant the time spent (in minutes) above the 3209 count/min cut-point, which defines the boundary between light (<4 METs) and moderate-to-vigorous (>4 METs) activity. The dependent variable was the mean time spent in moderate-to-vigorous physical activity across the two days (MVPA, min/day).

## Constitution of Physical Activity Groups

Physical activity score ( $z$ -score, calculated using means and standard deviations for the whole group) was calculated for each participant by averaging  $z$ -transformed data of the two dependent variables: present physical activity and past physical

activity. Then, sedentary and active groups were created using the median split of the physical activity score for each age group and each gender. The physically active participants were characterized by regular involvement in a high volume of physical activity that was typically of a sufficient intensity to produce a cardiovascular training effect. Conversely, sedentary participants were characterized by irregular involvement in any structured physical activity and typically reported less involvement in MVPA (See Table 1). According to the literature, they are considered physically sedentary (Thompson et al., 2009).

## Cardiovascular Fitness Evaluation

VO<sub>2</sub>max was estimated by the Rockport Fitness Walking Test (Kline et al., 1987). This submaximal field test was shown to accurately estimate VO<sub>2</sub>max in population such as the one of the current study (see Kline et al., 1987; McAuley et al., 2011). Participants were required to walk a timed mile (1609 m) as quickly as possible. Heart rate was continuously recorded by a beat-to-beat recorder, a Polar RS 800 (Polar Electro, Oy, Kempele, Finland). The VO<sub>2</sub>max was calculated using the equation developed by Kline and collaborators.

## Evaluation of Global Cognition

All participants were assessed with a comprehensive cognitive test battery. The global cognitive evaluation included the Letters Comparison Test assessing processing speed (Clarys, Isingrini, & Gana, 2002), the Digit Symbol-Substitution Test (DSST) from the WAIS III (Wechsler, 2000), the French Version of the Mill–Hill Vocabulary Test (Part B) (Deltour, 1993) and the French Version of the MMSE (Hébert et al., 1992).

## Evaluation of Executive Functions

Each of the three executive functions was assessed through three different computerized or paper and pencil tasks. All the computerized tasks were programmed and administered using E-Prime 1.1 software (Psychology Software Tools, Pittsburgh, PA). Below, we briefly present the experimental tasks used in this study.

### Shifting Function

**The Digit-Letter Task.** This paper and pencil task is described more in detail elsewhere (e.g., Clarys, Bugajska, Tapia, & Baudouin, 2009). A number-letter pair (e.g., 5A) was presented in one of four boxes of a table. Participants were instructed to indicate whether the number was odd or even when the number-letter pair was presented in one of the top two boxes (number task), and whether the letter was a vowel or a consonant when the number-letter pair was presented in one of the bottom two boxes (letter task). The number-letter pair was presented only in the top two boxes for the first list, only in the bottom two boxes for the second list, and randomly in all four boxes for the third list (switch trials). In all trials, all participants responded by ticking one answer from a choice of four: “Odd,” “Even,” “Consonant,” or “Vowel.” The dependent measure was the shifting cost, calculated as the difference in seconds between the time to complete the third list and the average of the times to complete the first two lists.

**The Plus-Minus Task.** This paper and pencil task, described in detail elsewhere (Miyake et al., 2000), consisted of three lists of 30 two-digit numbers. On the first list, the participants were told to add 3 to each number and to write down the answers on a board paper. On the second list, they were told to subtract 3 from each number. In the third list, they were told to sequentially alternate between adding 3 and subtracting 3 from the numbers. They were instructed to complete each list quickly and accurately, and completion times were measured. The dependent measure was the shifting cost in seconds, calculated by subtracting the mean total time on addition-only and subtraction-only lists from the total time on the alternating list.

**The Dimension-Switching Task.** This computerized task was described in detail elsewhere (Albinet et al., 2012). The stimuli were the French words for LEFT or RIGHT enclosed in a left or right arrow, and displayed above or below the center of the white screen. Depending on the location of the stimulus, participants were to perform either the word task or the arrow task (counterbalanced across participants). On word-task trials, participants made a button press in the direction indicated by the word. On arrow-task trials, participants responded according to the direction indicated by the arrow. There were two kinds of blocks of trials. On *simple blocks*, the stimulus appeared always on the same location, requiring only to respond to one task at a time. On *mixed blocks*, the stimulus could appear above or below the center of the screen, requiring to switch from one task to another task. The dependent measure was the global cost for correct responses, calculated as RT difference (in milliseconds) between trials from the simple blocks and from the mixed blocks.

## Inhibition Function

**Simon Task.** A measure of inhibition was obtained in the simple blocks of the dimension-switching task described above, where congruent and incongruent stimuli were presented. Congruent stimuli refer to those stimuli where both arrow and word afforded the same response (e.g., the word RIGHT within an arrow pointing to the right), as opposed to incongruent stimuli where arrow and word afforded different responses (e.g., the word RIGHT within an arrow pointing to the left). The interference effect—that is, the average differences in RTs (in milliseconds) between incongruent and congruent trials for correct responses across the simple blocks—served as the dependent measure.

**Random Number Generation Task.** This task is described in detail elsewhere (Audiffren, Tomporowski, & Zagrodnik, 2009). Briefly, participants had to say a number from 1 to 9 aloud each time they heard a computer-generated tone every 1 s, such that they generated a string of numbers that would be as random as possible. After a training period, 100 responses were recorded (usually during 100 s) and then analyzed using Towse and Neil's RgCalc software (1998). Successful performance on this task requires the participant to inhibit overlearned schemas (i.e., counting). The dependent measure was the total adjacency score. Adjacency describes the distribution of adjacent digits (in ascending or descending series) from the ordinal sequence of alternatives (i.e., 1–2; or 8–7–6) and is expressed as a percentage score. Adjacency scores range between 0% (no neighboring pair) and 100% (only neighboring pair).



**Stroop Task.** This paper and pencil version of the Stroop task is described in detail elsewhere (Clarys et al., 2009). This task involves three conditions. In the “word” condition, the words (e.g., French word for RED, BLUE, GREEN) were written in black ink. In the “color” condition, sequences of xxxx were written in red, blue, or green ink. In the “color-word condition,” the three color words systematically differed from the word’s ink color (e.g., French word for RED written in the color blue). Participants were required to read the words in the word condition and to name the ink color in the other conditions aloud as quickly as possible for 45 s, and the number of correct responses was recorded. The dependent measure was the interference score, as calculated by color-word score:  $[(\text{word score} \times \text{color score}) / (\text{word score} + \text{color score})]$ .

## Updating Function

**The Verbal Running Span Task.** In this computerized task (see Albinet et al., 2012 for a full description), lists of 6, 8, 10, and 12 consonants were presented on the computer screen at a rate of one letter every 2 s. Participants were asked to recall serially the last four items at the end of each list (strict forward serial recall). After four training lists, participants were presented 12 trial lists (three for each length). The dependent measure was the number of letters correctly recalled in the right order (max. = 48).

**The Spatial Running Span Task.** This computerized task (see Albinet et al., 2012, for a full description) is the spatial *equivalent* of the verbal running span. Sequences of 6, 8, 10, or 12 black dots were presented in 1 of the 16 cases of a  $4 \times 4$  empty matrix (no location was repeated in the same sequence), at a rate of one dot every 2 s. Participants were asked to recall serially the last four dots’ locations at the end of each sequence (strict forward serial recall) using the computer mouse. After four training sequences, participants were presented 12 trial sequences (three for each length). The dependent measure was the number of dots correctly recalled in the right order (max. = 48).

**The 2-Back Task.** This paper and pencil task, is described in detail elsewhere (e.g., Clarys et al., 2009). Participants listened to a continuous sequence of 30 letters (announced by the experimenter, at a rate of one every 2 s, and had to decide and say aloud whether each letter matched the one announced two positions back in the sequence. The dependent variable was the number of correct responses (max. = 28).

## Indicators of Executive Function Performance

Raw scores from each cognitive task were transformed into *z*-scores (using means and standard deviations for the whole group) (see Table A1 in the appendix to this article). When necessary, *z*-scores were transformed into their opposite so that a high score reflected better performance. To calculate a composite score for each postulated executive function component, a mean score was calculated from the *z*-scores of the cognitive tasks assumed to reflect the component. For each executive function component, a Cronbach alpha was computed to assess how well the selected tasks measured a single underlying construct. Alphas for each executive function component were moderate to good (.62, .72, .and 69 for inhibition, updating, and

shifting, respectively), indicating that each variable measured a one-dimensional latent construct.

## Procedure

The MMSE, the Mill–Hill vocabulary test, the letters comparison test and the Historical Leisure Activity Questionnaire were administered during a prescreening meeting. Subsequently, the participants performed the Rockport 1-Mile Walk Test to determine their cardiovascular fitness level. Finally, the participants were tested individually in a 2-hr session that was conducted in a quiet room of the laboratory. Executive tasks were administered in a counterbalanced order across participants.

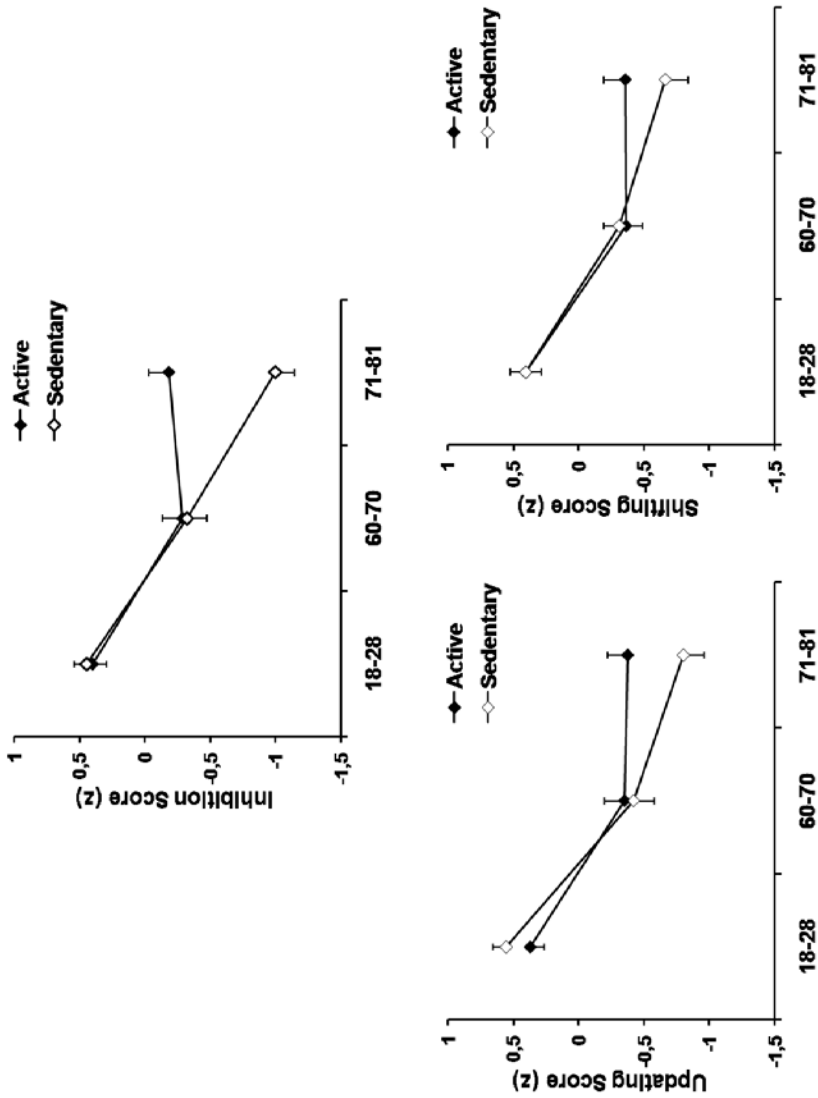
## Data Processing

This was a cross-sectional study with two independent variables: age and physical activity level. First, given that education level and body mass index (BMI) differed between active and sedentary groups (see Table 1), each of the three executive functions, that is, shifting, inhibition, and updating ( $z$  scores), was examined using separate analyses of covariance (ANCOVAs), with age group (young, young-old, old) and physical activity level group (active, sedentary) as between-subjects factors and years of education and BMI as covariates. Bonferroni post hoc tests were used to more precisely examine group differences when necessary. Second, we assessed the extent to which cardiovascular fitness ( $VO_2\text{max}$ ) accounted for the variance due to physical activity level in executive function performance, using hierarchical regression analyses. The relationship between physical activity, cardiovascular fitness, and cognitive performance, which can be conceptualized as a chainable link, was tested. The mediation model will be validated if the effect of physical activity score (continuous independent variable) on executive function (the dependent variable) can be “explained” by a third variable (the mediator), namely, cardiovascular fitness ( $VO_2\text{max}$ ). The following four criteria should be met (Judd & Kenny, 1981): (a) physical activity has a significant effect on executive function, (b) physical activity has a significant effect on  $VO_2\text{max}$ , (c)  $VO_2\text{max}$  has a significant effect on executive function, and (d) any physical activity effect on executive function does not remain significant after having controlled for  $VO_2\text{max}$ . The level of significance was set at  $p < .05$ . Partial estimated effect sizes ( $\eta_p^2$ ) were reported for significant results.

## Results

### Effect of Physical Activity on Executive Functions

The analysis revealed a main effect of age group for the shifting score,  $F(2, 115) = 22.24, p < .001; \eta_p^2 = .279$ , the inhibition score,  $F(2, 115) = 33.77, p < .001; \eta_p^2 = .37$ , and the updating score,  $F(2, 115) = 34.24, p < .001; \eta_p^2 = .373$ . Overall, as can be seen in Figure 1, the young adults group showed better executive performance than the two older adults groups ( $ps < .05$ ). Moreover, young-old adults had a better inhibition score than old adults ( $p < .05$ ). The Significant Age  $\times$  Physical Activity interaction (Figure 1) was exclusively observed for the inhibition score,  $F(2, 115) = 5.88, p < .003; \eta_p^2 = .103$ . Active old adults showed a better inhibition



**Figure 1** — Means and standard errors for the three executive functions as a function of physical activity level in the three different age groups; 18-28 = young adults, 60-70 = young-old adults, 71-81 = old adults.

performance than the sedentary old adults ( $p < .001$ ), whereas there was no effect of PA level within the two other age groups. Moreover, the inhibition score of the active old adults did not significantly differ from the one of active and inactive young-old adults ( $p > .05$ ). In contrast, the inhibition score of the sedentary old adults group was significantly lower than the one of the sedentary young-old adults ( $p < .001$ ). The Age  $\times$  Physical Activity interaction was close to significance for the updating score,  $F(2, 115) = 2.79, p = .07; \eta_p^2 = .046$ , but there was no sign for such interaction for the shifting score ( $F < 1$ ).

## Relationship Between Physical Activity, Cardiovascular Fitness and Executive Functions

As mentioned above, physical activity level was found to only positively impact the inhibition function in the old adults group. Therefore, we attempted to establish whether cardiovascular fitness was a mediator of this relationship.

First of all, a series of bivariate correlation analyses was run within the old adults group. As can be seen in Table A2, in the appendix, there were significant correlations between inhibition score, Mill–Hill score, age, and sex. This highlights the necessity to control for these confounding factors to isolate effects of physical activity score or  $VO_2\max$  in the regression analyses. To assess the association between physical activity score ( $z$ -score) and inhibition score ( $z$ -score), we led a hierarchical regression analysis in which the variables age, sex, and Mill–Hill score were firstly entered as predictors, physical activity score secondly entered as an independent predictor, and inhibition score as the dependent variable. The regression model was significant, with all four variables accounting for 50.5% of the total variance in inhibition score. Simultaneous entry of age, sex, and Mill–Hill score explained 38.9% of variance. The addition of physical activity score significantly increased the percentage of explained variance (11.6%):  $t = 2.42; \beta = .41; p < .05$ . In addition, the regression between  $VO_2\max$  and PA score was significant, with PA score predicting 45.7% of the variance of  $VO_2\max$ ,  $t = 4.87; \beta = .68; p < .01$ . Finally, we performed a hierarchical regression analysis to determine whether  $VO_2\max$  mediated the relationship between PA score and inhibition score. The variables age, sex, and Mill–Hill score were firstly entered as predictors,  $VO_2\max$  secondly entered as mediator, and physical activity thirdly entered as independent variable, with the inhibition score as the dependent variable. The  $VO_2\max$  significantly explained 15.6% of the variance of the inhibition score,  $t = 2.92; \beta = .68; p < .01$ , after controlling for age, sex, and Mill–Hill score. Physical activity score added a nonsignificant 3.3% of additional variance for the inhibition score,  $t = 1.37; \beta = .25; p > .05$ . To sum up, these hierarchical multiple regression analyses revealed that entering  $VO_2\max$  in the model explained the major part of the variance due to physical activity in the inhibition score and reduced this PA-related variance to a nonsignificant level. These results clearly indicate that  $VO_2\max$  mediated the positive influence of PA score on inhibition score in the old adults group.

Since the Physical Activity Level  $\times$  Age group interaction was marginally significant for updating score, we also performed the mediation analysis in the old adults group for this executive component, using the same procedure. Given the significant correlation between updating score and DSST (see Table A2, in the appendix), DSST score was entered as covariate in the hierarchical regression

analysis. While DSST score explained 24% of the variance, the addition of physical activity score did not significantly increase the percentage of explained variance (6.5%):  $t = 1.59$ ;  $\beta = .27$ ;  $p > .05$ . These results show that physical activity score did not predict updating score in the old adults group, precluding for performing the mediation analysis of  $VO_{2max}$ .

## Discussion

The present study examined the impact of physical activity on three executive functions in cognitive aging, and explored the potential mediator role of cardiovascular fitness in this relationship. Active participants exhibited a stable pattern of involvement in higher levels of physical activity by combining both past and present physical activity, whereas inactive participants were classified as physically sedentary. A set of three executive functions that are sensitive to age-related changes and selected within a well-known theoretical framework of executive functioning (Miyake et al., 2000) were assessed. Older adults were subdivided into two different age groups spanning 60–81 years of age. Our results reveal that physical activity level exerted heterogeneous effects on executive functions and was selective to the oldest people. Physical activity level was found to only positively impact the inhibition function (and to a lesser extent updating function) in our old adults sample. This specific effect on inhibition was shown to be mediated by cardiovascular fitness. Thus, higher levels of physical activity were associated with increased cardiovascular fitness among old adults group, which translated into better inhibition functioning.

A first element that deserves discussion is the largest association between cognitive performance and physical activity level among old adults. To date, few studies have attempted to examine whether the magnitude of physical activity effects on cognitive functioning varies across different age ranges within the elderly population. Some findings suggest largest benefits of physical activity at older ages (Renaud et al., 2010; Van Boxtel et al., 1997). For instance, in the Renaud et al. (2010) study, participants were divided by decades (60–69 and 70–79 years old) and by cardiovascular fitness level. Their results revealed benefits of cardiovascular fitness on execution of speeded motor responses only in the oldest group. Similarly, we showed that physical activity positively impacted cognitive performance only within the oldest age group. This pattern of results is consistent with the moderator model of Stones and Kozma (1988) assuming that the benefits of physical activity on cognitive performance are amplified with increasing age. The fact that older people have more limited cognitive resources and are less able to perform more complex tasks than younger adults would leave more room for improvement thanks to high levels of physical activity. In light of the current study and the previous results reviewed above, one might suggest that the more pronounced decline in inhibition function at the extreme end of the lifespan promotes the expression of the prophylactic effects of physical activity. However, some findings are in disagreement with ours. For example, Bunce & Murden (2006) showed that the beneficial effect of cardiovascular fitness on episodic memory decreased with advancing age along a continuum from 60 to 75 years. This discrepancy could be due to several methodological reasons, such as participants' mental or physical status (e.g., basic cognitive functioning,  $VO_{2max}$  level) and differences in the

complexity and response modes of the cognitive tasks. Future research is needed to examine the interaction between physical activity, age, and cognitive performance with comparable measures.

The selective effect of physical activity on inhibition function can be discussed with regard to the core role played by inhibition processes in the executive function construct. According to Miyake et al. (2000), executive functions can be considered as separable but related functions that share some underlying commonality. A possibility is that all executive functions involve inhibitory processes to operate effectively. Miyake et al. argue that the shifting function may involve suppressing the now-irrelevant task set to switch to a new task set and that the updating function may demand to suppress (or inhibit) obsolete information. Meanwhile, a large body of research shows that deterioration in inhibitory processes could play a central role in age-related declines in several different cognitive functions (see Hasher & Zacks, 1988). Taken together, these elements suggest that the inhibition function may be particularly sensitive to factors like age and/or physical activity level because of its elemental and ubiquitous properties in the executive function construct. Our finding seems to be somewhat inconsistent with other findings that physical activity level positively impacts shifting performance (e.g., Eggermont, Milberg, Lipsitz, Scherder, & Leveille, 2009; Tanaka et al., 2009). However, it should be noted that these studies are limited by the problem of “task impurity,” as they have used only one single task to assess shifting. In the current study, we used several different experimental tasks to examine physical activity effects at the more general level of the executive functions explored. Given the core role of inhibition on the executive function construct and the commonality shared by the different executive functions, one could also speculate that the positive effects of physical activity on other executive functions may be the consequence of the first impact on the inhibition process (Miyake et al., 2000). More research is now necessary to validate this possibility.

The results of the hierarchical regression analyses revealed that cardiovascular fitness mediated the benefits of physical activity level on inhibition in our old adults group. The influence of higher levels of cardiovascular fitness on cognitive aging might depend on the nature of the targeted cognitive function and its brain substrates. Older adults with higher cardiovascular fitness exhibit significant volumetric and functional improvements particularly in the right inferior frontal gyrus (rIFG) and the dorsal anterior cingulate cortex (Colcombe et al., 2004; 2006; Voelcker-Rehage et al., 2011). Interestingly, these brain structures underpin inhibition processes (see Aron, Robbins, & Poldrack, 2004; Braver et al., 2001). For example, the results obtained by Collette et al. (2006) support the major and specific role of the rIFG on inhibition processes. Importantly, Weinstein et al. (2012) recently revealed that gray matter volume of the rIFG mediates the relationship between higher cardiovascular fitness and Stroop interference in older adults. Hence, the functional network specialized in the function of inhibition could be preferentially boosted by the cardiovascular effects of physical activity. A challenge for future studies is to determine more precisely the neural mechanisms underlying this specific relationship.

The present study has several limitations. On a one hand, the cross-sectional design precludes inferences about causality in the relationship between chronic engagement in physical activity and inhibition function. Although previous studies have shown that physical training has beneficial effects on some executive functions (e.g., Albinet, Boucard, Bouquet, & Audiffren, 2010; Smiley-Oyen et al.,

2008), well-designed randomized, controlled trials are needed before a definite conclusion can be made. Nevertheless, the strength of our design was to compare individuals characterized by long established histories of exercise participation or nonparticipation. One might consider that these time periods are most likely to result in cardiovascular and cognitive improvements than short periods of physical activity. On the other hand, we estimated cardiovascular fitness indirectly by a submaximal field test, instead of a direct assessment with analysis of expired gases during a maximal effort protocol in a laboratory, for example. Nevertheless, one must note that previous studies have demonstrated that  $\text{VO}_2\text{max}$  estimation with the Rockport 1-Mile Test was highly correlated with direct measures of  $\text{VO}_2\text{max}$  and is thus suitable for this kind of research (Kline et al., 1987; McAuley et al., 2011).

To conclude, the results of the current study bring an essential contribution to the current literature, in clarifying the relationship between physical activity and cognitive aging. Of particular importance is that maintaining good cardiovascular fitness through a moderate-to-vigorous physically active way of life is associated with a relative preservation of inhibition capacities at an advanced age. These findings have practical significance in the context of an aging world, since the inhibition function is involved at old age both for instrumental activities of daily living (e.g., Vaughan & Giovanello, 2010) and social functioning (Von Hippel, 2007). This study is the first to clearly show that this relationship is particularly specific to the function of inhibition, instead of being generalized to all the executive functions investigated. This could explain some of the discrepancies in previous results concerning the effects of exercise on executive functions. Further research efforts can be directed toward establishing cause–effect and dose–response relationships between physical activity, cardiovascular fitness, brain functioning, and inhibition function through interventional designs and neuroimaging studies.

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## Appendix

**Table A1 Raw Scores on the Cognitive Tasks as a Function of Age and Physical Activity Level**

|   | Young Adults |              | Young-Old Adults |               | Old Adults    |               |
|---|--------------|--------------|------------------|---------------|---------------|---------------|
|   | Active       | Sedentary    | Active           | Sedentary     | Active        | Sedentary     |
| Processing speed <sup>a</sup>                       | 35.2 ± 5.8   | 35.0 ± 5.4   | 26.4 ± 5.0       | 24.3 ± 6.0    | 23.8 ± 4.4    | 24.3 ± 5.1    |
| “Simon” interference cost (ms) <sup>a,b,c</sup>     | 28.8 ± 23    | 37.3 ± 30.3  | 106.3 ± 58.3     | 82.8 ± 32.3   | 87.7 ± 72.5   | 181.2 ± 118.3 |
| Stroop interference <sup>a,b</sup>                  | 6 ± 6.4      | 3.8 ± 8.1    | 0 ± 6.9          | -2.2 ± 3.9    | -1.3 ± 5.4    | -8.7 ± 7.8    |
| Adjacency (%) <sup>a,c</sup>                        | 35.2 ± 11.9  | 30 ± 9.3     | 37.9 ± 8.2       | 43 ± 11.5     | 37.9 ± 10     | 42.7 ± 10.3   |
| Digit-letter shifting cost (s) <sup>a</sup>         | 22.6 ± 8.6   | 26.1 ± 10.3  | 36.9 ± 20        | 36.7 ± 12     | 35.1 ± 23.9   | 49.4 ± 32.4   |
| Plus-minus shifting cost (s)                        | 25.6 ± 16.3  | 21.4 ± 11.8  | 30.7 ± 22.9      | 30 ± 17.5     | 28.6 ± 17.2   | 33.3 ± 22     |
| “Dimension switching” global cost (ms) <sup>a</sup> | 185.1 ± 99   | 217.3 ± 90.1 | 471.2 ± 180.9    | 545.3 ± 222.1 | 598.5 ± 222.1 | 625.9 ± 180   |
| Verbal running span (/48) <sup>a,c</sup>            | 38.4 ± 6.1   | 40.8 ± 5.1   | 32.9 ± 8.9       | 34 ± 7.8      | 35.1 ± 5.2    | 27.5 ± 8.1    |
| Spatial running span (/48) <sup>a</sup>             | 38.6 ± 7.3   | 39.5 ± 6.8   | 25.1 ± 9.6       | 22.7 ± 10.3   | 22.2 ± 11     | 17.9 ± 7.6    |
| 2-Back (/28) <sup>a</sup>                           | 25.2 ± 2     | 25.5 ± 2     | 24.7 ± 2.5       | 23.3 ± 2.2    | 23.5 ± 2.2    | 23 ± 3.4      |

*Note.* Values are mean ± SD.

<sup>a</sup>Main effect of age.

<sup>b</sup>Main effect of physical activity level.

<sup>c</sup>Age by physical activity level interaction.

**Table A2 Full Correlation Matrix Within the Old Group of Participants**

| Measure                | 1             | 2             | 3            | 4            | 5            | 6           | 7           | 8           | 9 |
|------------------------|---------------|---------------|--------------|--------------|--------------|-------------|-------------|-------------|---|
| 1. PA score            | —             |               |              |              |              |             |             |             |   |
| 2. VO <sub>2</sub> max | <b>.68**</b>  | —             |              |              |              |             |             |             |   |
| 3. Age                 | -.31          | <b>-.44*</b>  | —            |              |              |             |             |             |   |
| 4. Education           | .32           | <b>.36*</b>   | -.30         | —            |              |             |             |             |   |
| 5. Sex                 | <b>-.52**</b> | <b>-.75**</b> | .21          | -.30         | —            |             |             |             |   |
| 6. Mill-Hill score     | .21           | .31           | -.25         | <b>.58**</b> | -.15         | —           |             |             |   |
| 7. DSST                | .30           | .30           | .06          | .07          | -.11         | .21         | —           |             |   |
| 8. Inhibition          | <b>.59**</b>  | <b>.68**</b>  | <b>-.45*</b> | .35          | <b>-.41*</b> | <b>.43*</b> | .32         | —           |   |
| 9. Updating            | <b>.39*</b>   | <b>.40*</b>   | -.04         | .28          | -.21         | .13         | <b>.49*</b> | <b>.46*</b> | — |

Note. \* $p < .05$  when  $r > .35$ ; \*\* $p < .01$  when  $r > .45$ ; PA = physical activity; DSST = Digit Symbol Substitution Test.