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## ABSTRACT

It is well-known that processing speed and executive functions decline with advancing age. However, physical activity (PA) has a positive impact on cognitive performances in aging, specifically for inhibition. Less is known concerning intraindividual variability (iiV) in reaction times. This study aims to investigate the influence of PA and sex differences on iiV in inhibitory performance during aging. Healthy adults were divided into active and sedentary groups according to PA level. To analyse iiV in reaction times, individual mean, standard deviation and the ex-Gaussian parameters were considered. An interaction between activity level and sex was revealed, sedentary females being slower and more variable than sedentary men. No sex differences were found in the active groups. These results indicate that the negative impact of sedentariness on cognitive performance in older age is stronger for females. The present findings underline the need to consider sex differences in active aging approaches.

## Introduction

It is well known that processing speed (e.g., Salthouse, 1996, 2000) and executive functions (e.g., Braver & West, 2008; Salthouse, Atkinson, & Berish, 2003) decline with advancing age in adulthood. Inhibitory processing can be particularly compromised and is thought to influence cognitive performance in a variety of cognitive domains (Hasher & Zacks, 1988; Lustig, Hasher, & Zacks, 2007). However, the amplitude of these age effects varies across cognitive domains, tasks, and individuals (Li, Huxhold, & Schmiedek, 2004; Lindenberger & Baltes, 1997; Lövdén, Li, Shing, & Lindenberger, 2007; Shaie, 1990). Moreover, differences across individuals can be larger than differences within a specific age group for a given cognitive domain or task (e.g., De Ribaupierre et al., 2013). Schaie (1990), for example, observed a clear decrease in mean

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cognitive performances across an average length of 7 years, but more than 50% of the individuals did not present any significant decrease. More recently, Yu et al. (2015) further demonstrated that decliners over a 7-year interval, compared with no decliners, had more depressive symptoms, were more socially isolated, and less engaged in cognitive or physical activities.

Several biological, behavioral, and environmental factors contributing to predict individual differences in the trajectories of cognitive change have been identified. Those factors either preserve or enhance the functional capacity of an older individual (see Hertzog, Kramer, Wilson, & Lindenberger, 2008, for an overview). In terms of biological factors, the presence of chronic diseases (e.g., cardiovascular diseases) is associated with altered brain function (e.g., reduced cerebral blood flow) or structure (e.g., loss of brain cells, white matter lesions; Stern, 2009) and with lower cognitive performance and cognitive decline (Carmichael, 2014; Denny, Kuchibhatla, & Cohen, 2006; Farag et al., 2011; Pigott et al., 2015; Reijmer et al., 2012; Seliger et al., 2004). But changes in brain function and structure are associated with compensatory mechanisms which contribute to increase individual differences during cognitive aging (see Stern, 2009). Further, polymorphisms in several candidate genes have been found to be strongly associated with the release and speed of developing specific age-related pathologies but also with individual differences in plasticity mechanisms and longevity (Deary, Whiteman, Starr, Whalley, & Fox, 2004; Lindenberger et al., 2008).

In terms of behavioral factors, research on cognitive training has revealed partly remarkable enhancement effects (e.g., Borella, Carretti, Riboldi, & De Beni, 2010; Borella, Carretti, Zanoni, Zavagnin, & De Beni, 2013; Rebok et al., 2014; Schmiedek, Lövdén, & Lindenberger, 2010), even if longer term benefits on everyday functioning and cognition are disputable. Moreover, and importantly for the present paper, research has demonstrated stronger evidence for the protective and restorative potential of physical activity (PA) and fitness on age-related cognitive decline and neurodegenerative diseases including Alzheimer's disease (e.g., see Colcombe & Kramer, 2003, for a review; see also Abou-Dest, Albinet, Boucard, & Audiffren, 2012; Albinet, Boucard, Bouquet, & Audiffren, 2010; Boucard et al., 2012; Buchman et al., 2012; Hamer & Chida, 2009; Li & Siegrist, 2012; Smith, Gardner, Fisher, & Hamer, 2015; Sofi et al., 2011; Tolppanen et al., 2015). However, significant gaps remain in the understanding of how PA and fitness protect the brain from adverse effects of brain aging. Further, promising results have been more recently shown based on studies combining cognitive and physical activities (Anderson-Hanley, Maloney, Barcelos, Striegnitz, & Kramer, 2016; Desjardins-Crépeau et al., 2016; see also Bherer, 2015; Zhu, Yin, Lang, He, & Li, 2016, for critical reviews).

In terms of environmental factors, stress is certainly among the most studied factors enhancing the vulnerability of the brain to aging (Peavy et al., 2012). Subjective feelings of loneliness and social isolation have also been identified as a major risk factor for cognitive declines and premature mortality (e.g., Antonucci, Fuhrer, & Dartigues, 1997; Baeriswyl, 2016; Ghisletta, Bickel, & Lövdén, 2006; Ihle et al., 2015). By contrast, education is one of the most widely studied and influential protective factors. Indeed, higher educational attainment and childhood IQ are associated with higher performance in multiple cognitive domains in old age (Fritsch, Larsen, & Smyth, 2007; Gatz et al., 2001; McDowell, Xi, Lindsay, & Tierney, 2007). Other protective factors could play an

undisputed critical role, such as personal characteristics of the individual (e.g., functional activities and autonomy, physical and mental health), physical environmental factors (e.g., facilities and amenities), socio-environmental factors (e.g., levels of social and recreational activity, family and social network), and socioeconomic factors (e.g., income, socioeconomic status) (see National Research Council (US) Committee on Aging Frontiers in Social Psychology, Personality, and Adult Developmental Psychology, 2006). Engaging in specific activities (social, physical, and/or cognitively demanding) can improve cognitive performance (e.g., Hertzog et al., 2008; Hillman et al., 2006; Holtzman et al., 2004; Hultsch, Hammer, & Small, 1993), slow down cognitive decline (e.g., Béland, Zunzunegui, Alvarado, Otero, & Del Ser, 2005; Hamer & Chida, 2009; Sturman et al., 2005; Wang et al., 2013; Weuve et al., 2004), and delay the onset of dementia and other common age-related brain diseases (Crowe, Andel, Pedersen, Johansson, & Gatz, 2003; Karp et al., 2006; Laurin, Verreault, Lindsay, MacPherson, & Rockwood, 2001; Wilson et al., 2002). As an example, Fratiglioni, Paillard-Borg, and Winblad (2004) showed that for all kinds of activities, there is a benefit on cognition, but this benefit is not the same. In particular, Jopp and Hertzog (2010) found that private social activities are more related to cognition that public social activities. Also, Gow, Mortensen, and Avlund (2012) demonstrated that physical activities better predict cognitive change than leisure activities.

Given the encouraging data on PA and cognitive aging (Hillman et al., 2006; see also Paillard, 2015, for a review), one major target for research in this area is to better understand and explain the nature of this relationship in more fine-grained detail. Therefore, we will focus specifically, in this article, on the impact of PA on inhibitory control in elderly as this represents one key cognitive process affected by aging. In general, the practice of regular PA improves or maintains cognition (e.g., Voelcker-Rehage & Niemann, 2013), executive functions, and particularly inhibition tasks performance (e.g., Albinet, Boucard, Bouquet, & Audiffren, 2012; Boucard et al., 2012; Colcombe & Kramer, 2003; Colcombe et al., 2004). Moreover, it has been shown that the benefit of PA is higher in the elderly compared to young adults (Boucard et al., 2012; Hillman et al., 2006; Newson & Kemps, 2006). Van Gelder et al. (2004) found that people who decrease the level of daily PA showed a greater cognitive decline compared to people maintaining their level of activity. Karceski (2012) further demonstrated that the risk of developing Alzheimer's disease is twice as large for an inactive person compared to an active one (see also Abe, 2012; Buchman et al., 2012; Hamer & Chida, 2009).

However, a number of important questions regarding the detailed nature of this relationship still remain unclear. As a first issue, little is known about the sex-specific effects of PA on cognitive aging. This is of great significance as older women are generally less active than older men (e.g., Centers for Disease Control and Prevention (CDC), 2002; Lee, 2005) and engaged less frequently in PA in later life (e.g., Kaplan, Newsom, McFarland, & Lu, 2001). However, to our knowledge, few studies (e.g., Lee, 2005) have investigated so far the effect of sex differences directly. Either physical activities were studied separately for men and women (e.g., Wannamethee, Shaper, & Walker, 1998; Yaffe, Barnes, Nevitt, Lui, & Covinsky, 2001) or the sex effect was controlled (e.g., Bielak, Gerstorf, Anstey, & Luszcz, 2014). The positive effect of PA on cardiovascular health was demonstrated in men (Wannamethee et al., 1998) and women (Kushi et al., 1997) separately. Yaffe et al. (2001) showed that PA prevents the cognitive decline in older women and Van Gelder et al. (2004)

found the same results in men (see also the meta-analysis from Colcombe & Kramer, 2003). Further, Blankevoort et al. (2013) demonstrated that walking ability and balance were significant predictors of cognitive performance for men, whereas only walking ability was significant for women, suggesting that the relationship between cognitive and physical performances is moderated by sex differences.

A second issue, and an original contribution of present article, concerns the differential effects of PA on various processing components of a cognitive task. In other words, most studies have commonly used standardized neuropsychological tests only providing mean level performance as outcome measures of memory or executive functions. Little empirical evidence is available concerning the association between PA and intraindividual variability (iiV) in cognitive performance. As suggested by Nesselroade (1991), iiV refers to individual systematic variations in short-term behavior that is moment-to-moment or item-by-item fluctuations in task performance. It provides additional complementary information that can be potentially masked by analyses based on mean performance levels. Transient short-term fluctuations in reaction times (RT) have been shown to increase with aging in adulthood (e.g., Li et al., 2010; 2004; see also Nelson & Dannefer, 1992) and to predict long-term decline in some cognitive skills, dementia, or even death (Hultsch, MacDonald, Hunter, Levy-Bencheton, & Strauss, 2000; Lövdén et al., 2007; MacDonald, Nyberg, & Bäckman, 2006). Interestingly, increasing iiV in RT is associated to executive dysfunctions (Bellgrove, Vance, & Bradshaw, 2003; West, Murphy, Armilio, Craik, & Stuss, 2002) and inhibitory inefficiency (Chuah, Venkatraman, Dinges, & Chee, 2006).While iiV has captured attention in the field of cognitive aging for the last decade, less is known about the link between iiV and PA or physical fitness. As examples, Bunce (2001); Bunce and Birdi(1998); and Bunce, Warr, and Cochrane (1993) considered that additionally, unusually slow latencies in choice RT tasks could be interpreted as indices of greater variability in performance. They further showed that older less fit men underperformed older fitter men and younger adults regardless of their fitness level. However, the strength of this interaction did not increase as a function of task complexity (two, four, and eight choices RT tasks). In another study, they found that greater age is more strongly associated with impaired cognition among less fit men than it is among more fit ones. Indeed, this relation was significant with respect to the occurrence of exceptionally slow responses but was not significant for mean RT. Furthermore, Bauermeister and Bunce (2016) found that lower aerobic fitness was associated with greater iiV in RT in different domains (immediate recognition, psychomotor performance, and executive function). This relation increased with age and was additionally mediated by executive function.

In summary, this study investigated the relationship between PA and sex differences and iiV in inhibitory performance during aging. The originality of the present work is twofold: on the one hand, to compare directly two groups of men and women according to the level of PA (active vs. inactive) and, on the other hand, to investigate the combined contribution of PA and sex differences on iiV in inhibition performance for the first time as your knowledge.

## Method

### Study

The current study used data from the "PRAUSE" project conducted in the region of Poitou-Charentes, France, from 2011 to 2013. This interdisciplinary research project targets the determinants of autonomy of noninstitutionalized older adults (see Audiffren et al., 2012 for more details). Four hundred and sixty-six retired volunteers aged 55 years and older (mean age = 75.7; SD = 9.8) were included in the project. A probability sampling method was used by the National Institute of Statistics and Economical Studies that guaranteed that the selected sample was representative of the population of healthy older adults in Poitou-Charrentes. Inclusion criteria were as follows: (a) being aged 55 years and above; (b) being retired, unemployed or on leave for a long duration, or at home; (c) being French native speakers; (d) not being institutionalized or placed in nursing or residential care facilities for disabled or dependant elderly persons; (e) not being placed under guardian or trusteeship; (f) having a high probability of the absence of dementia as indicated by a score equal or greater than 24 on the Mini Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975).

All participants gave written informed consent to participate to this project which was approved by two national ethics comities: (1) the project received the "general interest and statistical quality" label from the "Conseil National de l'Information Statistique" [French National Council of Statistical Information] (Visa no. 2012X907RG); (2) the project also received authorization no. 1593815 from the "Commission Nationale de l'Informatique et des Libertés" [French National Commission on Informatics and Liberty].

The study protocol was administered at home across three sessions, with a duration of 1.5–2 h each. During these sessions, a battery of cognitive tests and questionnaires (see below for details) was administered.

### Participants

One hundred and fifty-eight healthy volunteers (aged from 55 to 91 years; 89 females, 69 males; M = 71.9, SD = 9.0) of the 466 volunteers were included in the current analyses as they had completed all tests and questionnaires required to test the hypotheses developed above, and all of them had healthy vision (with correction or not). Participants were divided into women and men and physically active and inactive groups according to their current PA level, based on their responses on two questionnaires: the NASA/JSC Physical Activity Scale (PAS) and the Historical Leisure Activity Questionnaire (HLAQ) (see below for details).

### Materials

#### PA questionnaires

During the first session, all participants were asked to rate their regular weekly PA on a score from 0 to 7 with the *NASA/JSC PAS* (Jackson et al., 1990) to identify their level of current (i.e., the present year) PA. We used these data to determine the participants' PA

levels in case they left the study after the first session although this measure determines the level of PA somewhat less optimally than the subsequent questionnaire that was completed in the second session. Yet, it was used to include a maximum of participants. Participants classified by this method were considered active if their NASA/JSC PA score was higher than 3. Participants were classified as inactive if their NASA/JSC PA score was equal or lower than 3.

During the second session, the level of current PA was evaluated with the *HLAQ* (Kriska et al., 1988). This questionnaire assesses the level of PA weighted by its relative intensity. Participants were asked to report the frequency, type, intensity, and hours of PA performed during the present year. Using the Compendium of Physical Activity Tracking Guide 2011 (Ainsworth et al., 2011), we obtained a specific metabolic equivalent for each PA. According to the HLAQ data and the compendium, we calculated the average energy expenditure (Mets-h/week) for each participant.

Combining both data sources wherever possible (*n* = 425), according to the WHO recommendations, we classified participants as part of the active group participants whose PAS was above 3 and HLAQ above 7.5 Mets-h/week, and as part of the inactive group participants whose PAS was equal or below 3 and HLAQ equal and below 7.5 Mets-h/week.

### Cognitive task

Participants underwent a variant of the inhibitory arrow task (Salthouse, Toth, Hancock, & Woodard, 1997) in which a dominant response, strongly activated, must be suppressed to provide the correct answer. This task consisted of right (→) and left (←) pointing black arrows presented along the medial-horizontal axis of a computer screen in one of two locations (left or right). Participants were required to indicate the direction to which the arrow pointed independently of its spatial location. All stimuli were presented on a grey background screen. This gave rise to two stimulus types (congruent and incongruent) defined by the relationship between the location and direction of each arrow (same or opposite, respectively). Stimuli were equally distributed across location and direction.

Two blocks of 300 continuously presented trials each were administered, one homogeneous block of only congruent stimuli and one heterogeneous block of congruent and incongruent conflictual stimuli, with 33% (*n* = 100) of the later type. The order of the trials within the block was identical across participants and randomized except for the following constraints: no more than three consecutive simples left-right alternations (i.e., lc, right congruent (rc), lc, rc, lc, rc, …); no more than three consecutive double alternations (i.e., left-left-right-right-left-left,…), and, for the heterogeneous block, no more than two consecutive trials belonged to the same stimulus (i.e., left congruent (lc), lc,…). The order of the blocks within the task was counterbalanced across individuals.

The session started with six practice trials, with stimuli and timing identical to those of the experimental block. On each trials, the following sequence of events occurred: a black fixation point appeared at the center of the screen for a mean duration of 500 ms, varying randomly between 300 and 700 ms with a 100-ms incremental step. The stimulus (arrow pointing to the left or right) appeared on the right of left side of the screen and remained until the onset of the participant's response. Afterwards, the screen

went blank for 1000 ms following the onset of the participant' response or after a maximum of 2500 ms. Only correct response latencies were analyzed and RT below 150 ms were eliminated from all analyses. All the participants performed above 50% accuracy.

The inhibition task was conducted as part of the third session in the PRAUSE study. All testing was conducted individually in a quite location at home. Each experimental block lasted 10 min, with a total of 25 min for the cognitive task. The session lasted 1 h as other tasks and questionnaires were included in the protocol (for more details, see Audiffren et al., 2012).

## Statistical analyses

Data from the heterogeneous block only of the arrow task were analyzed. First, analyses were conducted on the intraindividual mean (iM) and on the intraindividual standard deviation (iSD). Second, analyses were conducted on iSD computed for the 25% fastest responses (lower quartile, fast-iSD) and 25% slowest (highest quartile, slow-iSD). Third, an alternative approach such as fitting ex-Gaussian functions to item-by-item RT data was used to more precisely describe the shape of individual RT distributions. The ex-Gaussian approach decomposes individual RT distributions into three parameters representing different parts of the curve: $\mu$ and $\sigma$ (representing the mean and standard deviation of the Gaussian component, respectively), as well as $\tau$, representing both the mean and standard deviation of the exponential component. These parameters are assumed to be linked to different cognitive processes and provide insights into psychological processes at work in the task (Heathcote, Popiel, & Mewhort, 1991; Spieler, Balota, & Faust, 1996, 2000). For example, the Gaussian component has been suggested as a marker of more stimuli driven, automatic processes in relative simple task, whereas the exponential component may represent more central attention demanding processes (i.e., $\tau$ being associated with lapses of attention). They are particularly useful for characterizing the nature of increasingly large iiV in impaired states and pathological conditions (see Leth-Steensen, Elbaz, & Douglas, 2000; for ADHD; Kieffaber et al., 2006; for schizophrenia; Tse, Balota, Yap, Duchek, & McCabe, 2010; Balota et al., 2010; for Alzheimer disease). The ex-Gaussian parameters ($\mu$, $\sigma$, $\tau$) were estimated using the statistical package quantile maximum probability estimator (Cousineau, Brown, & Heathcote, 2004; Heathcote, Brown, & Mewhort, 2002) which provides exit code (e.g., information about convergence properties, Hessian singularity) indicating whether the estimated solution is acceptable. The ex-Gaussian analyses require at least 40 valid RTs. Analyses were conducted only on cases with acceptable solutions. In the present sample, all individual RT distributions were acceptable. For more details on this method, see Fagot, Dirk, Ghisletta, and De Ribaupierre (2009) and Borella, De Ribaupierre, Cornoldi, and Chicherio (2013).

## Results

### Sample characteristics

Physically active and inactive groups did differ in terms of sex differences distribution, $\chi^2$ (1) = 4.1, $p$ < .05, indicating that inactive men are less represented. The four groups (i.e., women

inactive, women active, men inactive, and men active) did not differ in terms of global cognitive status as measured by the MMSE. Women and men differed in terms of depression measured by the Geriatric Depression Scale (30 items), $F(1, 151) = 16.42, p < .001, \eta^2 = .10$, with women reporting more depressive symptoms than men. However, this sex effect did not interact with PA. Physically active and inactive groups differed in terms of age, $F(1, 151) = 8.5$, $p < .005, \eta^2 = .05$, with inactive participants being older than the active ones. Women and men did not differ in terms of age. PA and sex interacted in terms of number of years of education, $F(1, 151) = 6.1, p < .05, \eta^2 = .04$. This interaction reflected that physically inactive men were more educated than the inactive women ($p < .05$) and that inactive men are more educated than active men ($p < .05$). Demographic characteristics are displayed in Table 1.

## Inhibitory control

ANCOVAs were conducted using PA level and sex differences as between-subjects factors and inhibitory task condition (incongruent vs. congruent stimuli) as repeated measures factor while age, depression, and education were considered as covariates. Post-hoc comparisons were corrected using the Bonferroni procedure. Descriptive statistics are presented in Table 2.

## Accuracy

The condition × sex × activity level interaction was significant, $F(1, 148) = 6.1, p < .05$, $\eta^2 = .04$, revealing that the activity effect on cognitive performance was significant only for women and in the incongruent condition ($p < .05$). In other words, active women were more accurate in their responses than inactive women when incongruent stimuli were presented. Moreover, inactive men were more accurate in their responses than inactive women for incongruent stimuli ($p < .05$). Furthermore, the condition effect that is worse performance for incongruent compared to congruent stimuli was significant for both sex and levels of PA (all $p < .05$). There was also a trend toward significance for a main effect of sex, $F(1, 148) = 3.0, p = .08, \eta^2 = .02$. No other effects were significant.

**Table 1.** Participants' sample characteristics.

| Groups | Women | | Men | | Significant effect |
|---|---|---|---|---|---|
| | Active | Inactive | Active | Inactive | |
| Participants (n) | 42 | 46 | 43 | 24 | |
| Age (years) | 69.4 (9.0) | 75.1 (9.7) | 70.3 (7.5) | 73.1 (8.3) | PA |
| Education level (years) | 11.2 (3.6) | 10.0 (3.4) | 10.4 (3.1) | 12.1 (4.1) | Sex × PA |
| MMSE | 28.2 (1.8) | 27.9 (1.7) | 28.3 (1.2) | 28.5 (1.6) | – |
| Depression | 7.9 (6.1) | 9.2 (5.1) | 5.5 (3.5) | 5.2 (3.3) | Sex |
| PAS (hours/week) | 7.5 (6.7) | .4 (.6) | 12.5 (7.9) | .4 (.7) | Sex, PA, sex × PA |
| HLAQ (Mets-hour/week) | 35.6 (38.1) | 1.7 (2.6) | 66.2 (44.8) | 1.4 (2.5) | Sex, PA, sex × PA |

Results are reported as the mean (and standard deviation) or row value. MMSE: Score at the Mini Mental State Examination; all participants scored greater than or equal to 24; Depression: score at the Geriatric Depression Scale (30 items); PAS: current physical activity level at the NASA/JSC Physical Activity Scale in terms of hours/week spent during regular weekly physical practice in the contemporary period; HLAQ: current physical activity level at Historical Leisure Activity Questionnaire in terms of estimated average energy expenditure (Mets-hour/week) spent in leisure's activities during the contemporary period; PA: significant main effect of physical activity (PA); sex: significant main effect of sex differences; sex × PA: significant interaction between PA and sex differences.

**Table 2.** Mean performance level and intraindividual variability as a function of sex differences, physical activity level, and stimulus type.

|  |  | Women | | Men | |
|---|---|---|---|---|---|
|  |  | Active | Inactive | Active | Inactive |
| Parameter |  | ($n = 42$) | ($n = 46$) | ($n = 43$) | ($n = 24$) |
| Congruent | Pcor | 97.7 (5.6) | 97.1 (4.4) | 98.6 (2.1) | 98.7 (1.6) |
|  | MRT | 604.7 (105.2) | 698.7 (136.7) | 591.4 (98.0) | 555.8 (995.3) |
|  | SDRT | 175.7 (71.2) | 226.0 (73.4) | 165.0 (62.3) | 148.8 (57.6) |
|  | 25% Faster SDRT | 40.5 (11.1) | 53.2 (23.8) | 41.1 (9.7) | 37.4 (9.6) |
|  | 25% Slower SDRT | 188.8 (88.6) | 240.7 (82.9) | 168.9 (90.6) | 144.9 (72.1) |
|  | Mu | 428.2 (80.2) | 473.0 (92.5) | 432.3 (78.6) | 418.4 (64.4) |
|  | Sigma | 77.8 (41.6) | 89.3 (39.8) | 77.3 (40.3) | 67.7 (29.4) |
|  | Tau | 176.5 (81.1) | 225.7 (74.2) | 159.1 (78.4) | 137.4 (65.6) |
| Incongruent | Pcor | 93.4 (7.4) | 88.2 (9.8) | 92.7 (6.9) | 93.4 (4.9) |
|  | MRT | 741.6 (156.5) | 902.0 (184.4) | 737.3 (155.9) | 683.3 (119.6) |
|  | SDRT | 186.2 (85.7) | 261.9 (94.1) | 180.2 (73.5) | 154.3 (67.8) |
|  | 25% Faster SDRT | 42.2 (14.9) | 55.5 (26.4) | 45.0 (24.7) | 42.7 (17.1) |
|  | 25% Slower SDRT | 182.9 (91.6) | 242.5 (84.0) | 184.4 (86.5) | 165.2 (91.1) |
|  | Mu | 566.4 (101.7) | 664.4 (141.6) | 569.9 (139.3) | 539.5 (92.0) |
|  | Sigma | 82.8 (49.8) | 127.0 (66.7) | 75.0 (61.5) | 71.9 (27.6) |
|  | Tau | 175.2 (85.6) | 237.6 (81.4) | 167.4 (73.6) | 143.8 (76.4) |

Results are reported as the mean (and standard deviation) or row value. Congruent and incongruent refer to the stimulus type.
Pcor: percent correct responses; RT: response times in milliseconds; 25% fastest/slowest: 25% of the fastest (or slowest) responses from the individual RT distribution; mu, sigma, and tau: parameters from the ex-Gaussian RT distribution.

## Classical indices: iM and iSD

The main effect of sex was significant (iM: $F(1, 148) = 16.1$, $p < .001$, $\eta^2 = .10$; iSD: $F(1, 148) = 15.3$, $p < .001$, $\eta^2 = .09$). Men were significantly faster and fluctuated less in their overall responses than women. The sex × activity level interaction was significant (iM: $F(1, 148) = 11.5$, $p < .001$, $\eta^2 = .07$; iSD: $F(1, 148) = 8.2$, $p < .005$, $\eta^2 = .05$). *Post-hoc* comparisons revealed that the sex effect was significant only for the inactive group ($p < .05$). Inactive men were faster and less variable than inactive women. Moreover, the activity level effect was significant only for women ($p < .05$). This effect suggests that active women were generally faster and fluctuated less in their responses than the inactive ones. It should be noted that for the iM, there was a trend toward significance for men ($p = .07$). Importantly, the sex × activity level × condition interaction was obtained for iM ($F(1, 148) = 6.3$, $p < .01$, $\eta^2 = .04$) and trend toward significantly for iSD ($F(1, 148) = 3.62$, $p = .06$, $\eta^2 = .02$). First, *post-hoc* comparisons revealed that the sex effect, whatever the inhibitory task condition, was only significant for inactive participants ($p < .05$). Second, the condition effect was significant whatever the activity level and for both sex (all $p < .05$). Finally, for women, across both inhibitory task conditions, the active ones were faster than the inactive ones ($p < .05$), and for men, there was just a trend ($p = .08$ for congruent stimuli; $p = .09$ for incongruent stimuli). Finally, for iM, there was a trend toward significant for the sex × condition interaction, $F(1, 148) = 2.9$, $p = .09$, $\eta^2 = .02$. It should be noted that when controlling additionally for the individual mean RT in the analyses of individual standard deviation, all the abovementioned significant effects did not survived.

## 25% Fastest (fast-iSD) and slowest (slow-iSD) responses times

The main effect of sex was significant (*fast*-iSD: $F(1, 148) = 4.3$, $p < .05$, $\eta^2 = .03$; *slow*-iSD: $F(1, 148) = 10.6$, $p < .05$, $\eta^2 = .07$). Men were significantly less variable than women. The

sex × activity level interaction was significant (*fast-iSD*: $F(1, 148) = 6.1$, $p < .05$, $\eta^2 = .04$; *slow-iSD*: $F(1, 148) = 5.4$, $p < .05$, $\eta^2 = .04$). *Post-hoc* comparisons revealed that the sex effect was significant only for the inactive group ($p < .05$). Moreover, the activity level effect was significant only for women ($p < .05$). Active women were less variable than the inactive ones. It should be noted that, for the 25% slowest responses, there was a trend toward significance for the condition effect, $F(1, 148) = 2.9$, $p = .09$, $\eta^2 = .02$. No other effects were significant.

### Ex-Gaussian parameters

The main effect of sex was significant for all parameters (*μ*: $F(1, 148) = 5.0$, $p < .05$, $\eta^2 = .03$; *σ*: $F(1, 148) = 10.7$, $p < .001$, $\eta^2 = .07$; *τ*: $F(1, 148) = 15.9$, $p < .001$, $\eta^2 = .10$). Men had a smaller mu, sigma, and tau than women. In other words, men were significantly faster, fluctuated less, and produced less extremely slow responses than women. The sex × activity level interaction was also significant for all parameter (*μ*: $F(1, 148) = 5.7$, $p < .05$, $\eta^2 = .04$; *σ*: $F(1, 148) = 4.8$, $p = .05$, $\eta^2 = .03$; *τ*: $F(1, 148) = 7.1$, $p < .001$, $\eta^2 = .05$). *Post-hoc* comparisons revealed that the sex effect was significant only for the inactive group ($p < .05$). Moreover, the activity level effect was significant only for women ($p < .05$). Active women were faster, less variable, and produced less extreme values (i.e., slow responses) than inactive ones. It should be noted, for $\sigma$, that there was also a trend toward significance for condition × sex interaction, $F(1, 148) = 2.9$, $p = .09$, $\eta^2 = .02$. Importantly, when controlling additionally for mu parameter in the analyses, all the abovementioned significant effects survived for $\tau$. No other effects were significant.

To sum up, the main results were (1) inactive women have worst performance than the active ones in the more resources demanding inhibitory condition, this effect is not found in men; (2) whatever the indices used, women appear to be slower and more variable than men; (3) whatever the indices used, the level of PA has an impact only in women; (4) inactive women are less accurate, slower, and more variable than inactive men, this effect is not found on the active ones. Figure 1 summarizes these findings based on ex-Gaussian distributional analyses.

### Discussion

According to previous research, women are more variable in their cognitive performances (i.e., RT) than men (e.g., Der & Deary, 2006) and, on the other hand, women are more sedentary than men (e.g., CDC, 2002; Lee, 2005). Therefore, "sedentary women" should be the most variable (and consequently the most vulnerable) group while active men should be the less variable group that is less likely to decline. Consistent with the literature, our results showed that women's cognitive performances show more inconsistency than men's. However, PA levels alone don't have a significant influence on cognitive performance; they interact with sex differences. As expected, inactive women are the most variable, suggesting that they are the most vulnerable and represent the group that accumulates disadvantages. Not being engaged in any PA has a more negative impact on the cognitive performance of women than on those of men. However, engaging in PA has the same positive impact on men and women. No differences where identified in mean performance and indices of variability between
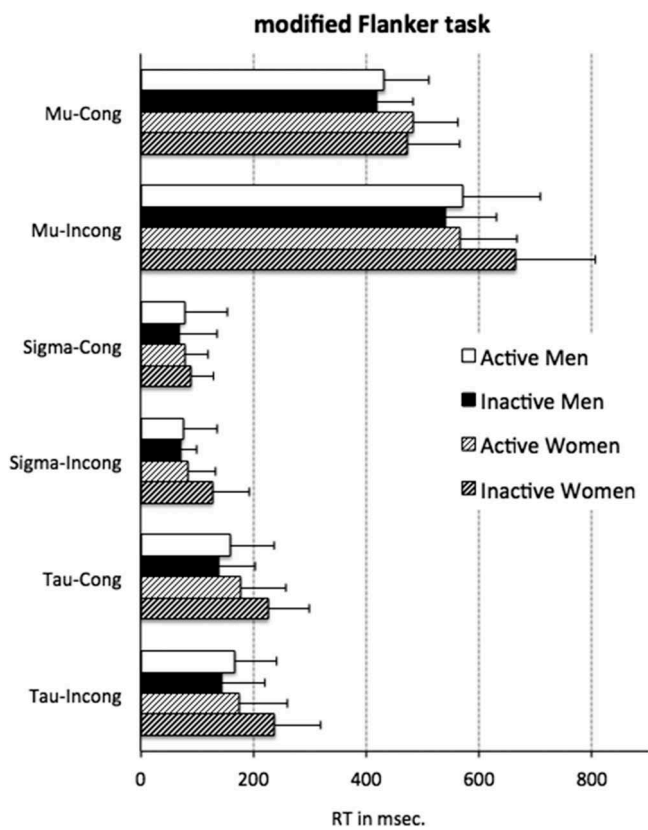
**Figure 1.** Effect of sex differences and activity level on different reaction time parameters in the modified Flanker task.

Mu: mean of the normal component of the individual RT distribution; sigma: standard deviation of the normal component of the individual RT distribution; tau: the mean and standard deviation of the exponential component of the RT distribution; cong: congruent condition; incong: incongruent condition. Error bars represent one standard error.

the two active groups. This finding suggests that engaging in PA is beneficial to all older people but that an absence of PA increases the vulnerability of women.

Previous meta-analyze studies (Barha et al., 2017; Colcombe & Kramer, 2003) have shown that women's cognitive functioning benefits more from regular PA than that of men. This sex difference in the benefits of PA on cognitive performance may be related to potential role of sex steroid hormones and BDNF (brain derived neurotrophic factors) signaling. For example, a complex interaction between the duration of estrogen-based hormone replacement therapy and physical fitness on cognitive performance and pre-frontal grey matter volume in older postmenopausal women has been shown, potentially linked to an increase in cerebral BDNF production (Audiffren et al., 2011; Erickson et al., 2007). Moreover, experiments with animals, along with a few recent studies of human, suggest that the link between BDNF level and cognition is greater for women than for men and that aerobic exercise induces greater increases in BDNF in females than in males (Barha et al., 2017; Komulainen et al., 2008). However, those results rely on a very limited number of studies and cannot directly explain why, in the present study,

women did not show greater cognitive benefits from PA than men, but only more vulnerability from inactivity. Clearly more work is needed to better characterize and understand this sex-effect on the relationship between physical (in)activity and cognition in older adults.

Beyond its inherent limitation, our study has undeniable advantages. To our knowledge, only one previous study has examined the relationship between sex differences and PA (Blankevoort et al., 2013) and little is known about this link and iiV. In addition, Bauermeister et al. (2016) explored the relationship between iiV (e.g., using the coefficient of variation, measured by the individual standard deviation divided by the individual mean) with the risk of falling in older adults. They claimed that iiV predicts falls via motor functions (e.g., gait). While promising, it is important to take these results further, in order to find out whether and how PA improves (or more generally influences) cognitive performances and particularly the iiV. This processing component of cognitive performance can be therefore regarded as an important source of information in addition to the mean (e.g., Nesselroade, 2002; Van Geert & Van Dijk, 2002) and does not simply represent measurement error (De Ribaupierre, 2015a, 2015b). Bielak, Hultsch, Strauss, Macdonald, and Hunter (2010) underlined that, regardless of the time of life considered, the iiV could be considered as an intrinsic characteristic of individual functioning (Lautrey, 2003). However, in this study, we demonstrated that not all iiV indices are adequate to show the added value of the mean. In fact, although all these indices showed the same outcome, when we controlled for the mean (iM or $\mu$), only the results on ex-Gaussian parameter ($\sigma$) remained significant. Therefore, the analysis of the shape of individual RT distribution (i.e., ex-Gaussian) seems to be more suitable than alternative, classical measures (iSD).

In the present study, we focus on executive functions, in particular inhibition, to investigate the impact of PA on iiV. The use of an inhibitory task is motivated by the fact that, on the one hand, this ability is particularly sensitive to aging and, on the other hand, executive functions are mostly influenced by regular PA (e.g., Albinet et al., 2012; Colcombe & Kramer, 2003; Colcombe et al., 2004). Nevertheless, only one task assessing one component of executive functions was administrated. Blankevoort et al. (2013) explored the relationship between physical and cognitive performances using inhibition and shifting tasks and they found that this link is relatively similar across tasks. Further research is needed to assess whether such results are confirmed and can be extended to other executive processes (i.e., updating), as suggested by some previous studies (Abou-Dest et al., 2012; Albinet et al., 2016).

As mentioned in the "Introduction" section, iiV in RT has been shown to increase with aging in adulthood, and to predict long-term decline in various cognitive abilities, dementia, or even death (e.g., Hultsch, MacDonald, & Dixon, 2002). It seems to be clear that iiV in aging has been viewed as dysfunctional (e.g., MacDonald & Stawski, 2015) and is often associated with vulnerability. Although the correct interpretation of an increase in iiV is unclear, a number of researchers have suggested that it is linked to attentional lapses, related to a lack of attention/ executive control, and represents a reliable indicator of the loss of integrity in the brain. Moreover, several authors have reported an increase in iiV associated with range of pathologies such as traumatic brain injury (Stuss, Pogue, Buckle, & Bondar,

1994), dementia (Hultsch et al., 2000), and neurodegenerative disease (Burton, Strauss, Hultsch, Moll, & Hunter, 2006).

RT and iiV in RT while processing visually presented tasks are heavily dependent upon cortico-subcortical networks that lie within regions of the brain that are sensitive to neuropathological changes to the aging brain. On the one hand, age-related reduction in occipitotemporal activity associated with visuo-perceptual processing in a variety of tasks has been consistently attributed to deficits in sensory processing (see Schneider & Pichora-Fuller, 2000, for a review) as a major factor in cognitive aging (Lindenberger & Baltes, 1994). On the other hand, more bilateral frontal activity in older adults (see Cabeza, 2002, for a review) has been associated with potentially compensatory mechanisms (see Cabeza, Anderson, Locantore, & McIntosh, 2002; Grady, McIntosh, & Craik, 2005; Reuter-Lorenz et al., 2000), which have been found to be coupled with decreased posterior occipital activity and neuroanatomical decline (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008). Furthermore, increasing iiV in RT is associated to executive dysfunctions (Bellgrove et al., 2003; West et al., 2002) and inhibitory inefficiency (Chuah et al., 2006). It relies upon fronto-striatal-cerebellar circuits (Castellanos & Tannock, 2002; Krain & Castellanos, 2006) and is presumably linked to altered dopaminergic modulation (Bäckman, Nyberg, Lindenberger, Li, & Farde, 2006). It has been shown that less behaviorally consistent individuals need to recruit the inhibitory control networks to a greater extent (Bellgrove, Hester, & Garavan, 2004). As such, inhibitory and more generally executive processes seem more solicited and less efficient with advancing age. Whether this increased and more bilateral frontal activity is attributed to successful, unsuccessful, or attempted compensation is still a matter of debate and ongoing studies in the literature. However, this brain activity is certainly accompanied with subtle functional, structural, and neurochemical modifications and reorganization occurring with advancing age.

However, as an inherent limitation, underlying brain pathology within these networks within our study sample cannot be excluded. The presence of grey and white matter lesions within the regions of the brain that contain these networks may have influenced the reported results. Unfortunately, structural brain images of the participants are not available in the present study, which could have helped to consider more appropriately, but not fully, this issue. Nevertheless, we could rely on a large representative sample of functionally independent, affectively stable, and cognitively preserved participants of different ages. In the present sample, further work may focus on the characterization and quantification of the presence of chronic diseases (e.g., cardiovascular diseases, type-2 diabetes, stroke, chronic respiratory diseases, neurological disorders, and hypertension) that may have influenced our results. It is undisputable that individual differences in cognitive performance increase from early to late adulthood (Hertzog et al., 2009), likely reflecting influences of a multitude of factors at different levels of analyses (e.g., biological, behavioral, and environmental). More interestingly, losses in brain resources in normal aging modulate the effects of common genetic variations on cognitive functioning. It may be of relevance to further investigate the impact of catechol-*O*-methyltransferase (COMT) gene polymorphisms which metabolize dopamine and are associated with prefrontal dysfunction and cognitive aging. These COMT effects can be modulated by the BDNF released during PA which enhances brain plasticity and consequently brain health.

Put together, potential gene–gene interactions extend recent evidence of close interactions between frontal and medial–temporal networks in executive functions (Lindenberger et al., 2008). Stronger genetic effects observed during aging, in that older individuals carrying disadvantageous genotypes show that disproportionate impairments of neural processing may help to understand the effect of PA in cognition. Last but not least, the current literature suggests that dynamic connections between a set of neural structures including the medial prefrontal cortex (see Shaffer, McCraty, & Zerr, 2015; see also Thayer & Lane, 2000; for the neurovisceral integration model), involved in cognitive, affective, and autonomic regulation, help regulate hearth rate variability and are related to cognitive and particularly executive performance. For example, Albinet and colleagues (2010) interestingly demonstrated improved executive performance and hearth rate function (i.e., increased variability) with an aerobic training in the elderly, suggesting its role as an important cardiac and brain protective factor. To this regard, executive function has a pivotal role for future studies on the relationship between PA, cardiac activity, and brain integrity during aging.

One limitation of this study could also be the use of self-administered questionnaires, instead of more direct observations, to measure the PA levels of participants. As detailed by Shephard (2003) and Vanhees et al. (2005), questionnaires rely on subjective, self-reported responses and their reliability and validity are dependent on the veracity and the precision of the respondent (based on the efficacy of their episodic memory, which, particularly in the case of older adults, may be altered). Their correlation with more direct measures of PA or physical fitness is often weak to moderate, although may nevertheless enable us to discriminate between "active" and "sedentary" groups, as in the present study. However, the use of questionnaires is the most convenient and adapted tool to qualify and quantify a behavior such as PA, among on large-scale populations and over a long period of time (several weeks or years) and we would argue that it offers a reliable estimate of a stable and regular way of life. Moreover, contrary to some studies, our work does not focus on one particular kind of PA (e.g., aerobics). From the questionnaire responses, we were able to estimate of the energy cost (according to the types of activity and their frequency), in order to distinguish between "sedentary" and "active" groups and to take into account the individuals resources (capacity). Indeed, not all the elderly can practice aerobic exercise, either for reasons of health or lack of motivation.

In conclusion, engaging in PA appears to be equally beneficial for healthy elderly men and women. However, the absence of PA is detrimental to elderly women, increasing their vulnerability or frailty. It is thus important to take the mediating role of sex differences into account, in order to refine strategies for prevention and health promotion, and to tailor prevention measures to the most at-risk groups (see Smith et al., 2015).

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## Disclosure statement

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