The Simon Task and Aging: Does Acute Moderate Exercise Influence Cognitive Control?

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Abstract

Purpose: This study aimed to investigate the influence of an acute bout of moderate exercise and examine the potential lasting improvements over time in young and old adults within the same experimental paradigm over a 2 hour testing period. The study was designed to assess the efficiency of selective control and the propensity to make fast impulsive reactions through the analyses of the percentage of correct responses (CAF) and the magnitude of the interference effect (delta curve) as a function of the latency of the response.

Methods: Twelve young (23±2 yrs) and 12 old (63±2 yrs) volunteers, performed the Simon task while cycling (30 minutes of cycling at 65% of age-predicted HR\textsubscript{max}) and after exercise cessation (post 5, post 35 and post 65 minutes).

Results: Results showed that exercise did not alter cognitive control. The benefit on reaction time performance was evident for both age groups and persisted after cessation for 15 to 20 minutes. Distributional analyses showed that younger people have a higher propensity to commit impulsive errors during exercise, which was not evident in older adults. Older adults adopted more cautious strategies, especially when the risk to commit an error was elevated. Despite the larger mean interference effect compared to younger adults, the pattern of the delta curves attests to the existence of an efficient cognitive control in older people.

Conclusion: This study illustrates the effectiveness of distributional analyses and supports the idea that exercise induced facilitation on cognitive performance can be realized across the lifespan. Future investigations should explore whether accumulated bouts of acute exercise could display an aggregate cognitive benefit which may significantly impact independent functioning in older adults.

Keywords: cognitive aging, inhibitory control, reaction time, distributional analyses, benefit, impulsive errors.
The growing segment of the population over 65 years of age has ignited an interest in research on cognitive function among older adults. Cognitive aging is a universal occurrence that affects many of those who survive to their older years (65+) and the incidence of cognitive impairment in the aging population remains one of the most common morbidities in the elderly. Consequently, the relationship between aging and cognition is of great interest. While it is accepted that advancing age is predictive of diminished cognitive performance on many tasks (28), a large variability on cognitive performance exists among this population which ranges from “successful cognitive aging”, on one end of a continuum, to pathological conditions such as Alzheimer’s disease on the other end. Given this variance, researchers have concluded that cognitive decline is not an inevitable consequence of aging and have started to identify lifestyle factors which may ameliorate this age-associated decline. One lifestyle factor that has received a lot of attention is physical activity.

Executive control processes which are dependent on the integrity of the prefrontal and frontal region of the brain for optimal efficiency appear to be strongly affected by age (35). Research has shown that older adults who participate in exercise interventions and improve their aerobic fitness experience cognitive gains for certain cognitive tasks (7). Research suggests that there are disproportionally larger cognitive gains to be realized on tasks requiring executive control following chronic exercise participation (11, 14, 19). While there is an abundance of research on the impact of chronic exercise in the elderly, there is unfortunately a great paucity of research investigating the influence of acute exercise and the lasting improvement following exercise cessation. Chronic exercise interventions are composed of a series of acute exercise bouts which justifies the investigation of what moderates the effectiveness of acute bouts of exercise at improving cognitive performance. It is still unclear how acute exercise responses (e.g., immediate elevations in blood flow, heart rate and oxygen uptake), when experienced
chronically attenuate age-associated cognitive decline. Moreover, considering that for most repetitive exercise training programs, gains are achieved during interspersed rest periods when no training occurs, examining what happens cognitively following exercise is an important subject matter which warrants investigation. A better understanding of the cognitive improvement observed while exercising and the persistent benefit following exercise would undoubtedly enhance exercise intervention designs as a means of combating age associated cognitive decline.

The existing literature supports a beneficial influence of acute exercise on cognitive performance in young adults (e.g., 6, 21), however it has not been established if this influence is similar across the lifespan and if it endures after exercise cessation. Kashihara and Nakahara (16) assessed the duration of the cognitive enhancement during a choice reaction time (RT) task after 10 minutes of cycling at lactate threshold. They showed that the positive effects of exercise lasted over 8 minutes post exercise but not thereafter. More recently, Joyce and colleagues (15) investigated the effect of 30 minutes of moderate exercise in young adults and showed that performance on a stop-signal task was facilitated during exercise. This improvement was sustained for up to 50 minutes after exercise cessation. Recently, Barella and colleagues (3) investigated the duration of cognitive improvements after an acute exercise bout in a healthy, older population performing a Stroop color-word interference task. Results showed an improvement in RT performances on the Stroop color test immediately after exercise, while no changes were observed in the Stroop test measuring the magnitude of the interference (i.e., the additional time needed for naming colors that conflicted with the written word). Examination of the enduring effects of exercise on cognitive performance was inconclusive. The authors concluded that 20 minutes of walking at

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1 In this task single words (including names of colors) are presented in colored ink, and the subject is required to name the color of the ink as quickly as possible. The ink color can either match or conflict with the color name. e.g. RT to the color red will be faster when the word red is written in red (congruent) compared to when the word blue is written in red (incongruent). Reaction time and accuracy are measured.
60% of age-predicted heart rate reserve (HRR)\(^2\) had transitory benefits on speed of information processing but did not alter cognitive control in this age group. It was also suggested that, the duration and intensity of the exercise used in this protocol may not have been the most appropriate for eliciting cognitive performance benefits in healthy older adults.

The present study aims to further investigate the influence of an acute exercise session (30 minutes of cycling at 65% of age-predicted HR\(_{\text{max}}\)) and the potential lasting improvement following exercise cessation in older and young adults within the same experimental paradigm. The design was optimized to allow the measurement of any observed change over the 2 hours, and permit the completion of a large amount of trials on a Simon task (about 4,000 trials) to investigate the temporal dynamics of information processing. An individual’s ability to inhibit incorrect response impulses is a crucial element of cognitive control, and can be assessed using the Simon task (29, 30). During this task, participants are required to respond, as quickly and accurately as possible, by selecting the relevant feature of the stimulus (the color) and inhibiting the irrelevant feature (the spatial location) of the same stimulus. Reaction time (RT) performances are usually reported to be worse (i.e., slower and less accurate) when relevant and irrelevant information are mapped to different responses (incongruent trials, IN), than when they correspond to the same response (congruent trials, CO). This phenomenon is known as the Simon effect (RT on incongruent trials minus RT on congruent trials) and is interpreted as resulting from a conflict between alternative responses. According to dual-route models of information processing (10,17,27), this finding results from a conflict between an automatic and rapid response impulse (triggered by the spatial location) and a slower, deliberately controlled response to the pertinent stimulus information (the color). More recently, a suppression component has been added to the dual-route model to further elucidate conflict resolution (for an

\(^2\) HRR corresponds to the difference between measured (or predicted) maximal heart rate (HR\(_{\text{max}}\)) and resting heart rate (HR\(_{\text{rest}}\))
overview, see (32)). The automatic activation is initially strong, but gradually decreases over time with the development of a slow and incremental inhibition. This suppression mechanism counteracts the automatic activation and facilitates the occurrence of the correct response. Through the analyses of the percentage of correct responses (conditional accuracy functions, CAF) and the magnitude of the interference effect (delta curve) as a function of RT, the activation-suppression model provides a powerful framework to assess conflict resolution. This model specifically allows for the assessment of both the initial phase linked to an individual’s susceptibility to making fast impulsive errors (early automatic response activation) and, the later phase associated with the efficiency of the cognitive control (build-up of a top-down response suppression mechanism) (32).

In earlier studies it was shown that, in young subjects, the beneficial effect of acute moderate exercise on RT can be sustained for a considerable amount of time after exercise cessation (15). The present study aimed to assess whether similar results could be obtained with older participants, and whether age-associated cognitive decline modifies the susceptibility of making fast impulsive errors and alters cognitive control efficiency. Distributional analyses of response errors and response speed were conducted to closely examine the temporal dynamics of information processing and to dissociate the activation of incorrect responses and its subsequent selective suppression. If older participants are less impulsive than the younger adults, fewer errors are expected for fast RT trials on distributional analyses of response errors. If the efficiency of cognitive control decreases by aging, the drop-off of the delta curve should be less pronounced on distributional analyses of response speed. The last objective of the present study was to determine whether sequential behavioral adjustments (between trials post-conflict and post-error adjustments) are sensitive to aging and interact with exercise, by assessing the dynamics of cognitive control according to the nature of the preceding trials during the Simon
task (10). If cognitive control is impaired by aging and interacts with exercise, post-conflict and post-error adjustments should be less sizeable or absent for older persons and fluctuate according to exercise conditions.

METHODS

Participants

Twenty-four participants (12 young: range 18-28 yrs; 12 old: range 60-70 yrs) completed this study. The anthropometrical and physiological characteristics of the participants are reported in Table 1. Participants were fully informed about the experimental protocol. All participants reported being free of adverse health conditions, neurological disorders and any medication that influences central nervous system function. This experiment was approved by the University ethics committee.

---------Insert Table about here--------------

Procedure

After providing informed consent, participants in this study reported to the laboratory for testing on three separate occasions. As the tests are influenced by circadian rhythms all testing for each participant was carried out at the same time of day.

Preliminary protocols.

After height, weight and blood pressure measurements were recorded, the procedure started with a sub maximal exercise test to predict maximal oxygen uptake ($\dot{V}O_2_{\text{max}}$). This progressive incremental protocol conducted on a cycle ergometer (MONARK 828 E, Sweden) began with participants cycling at 30 W. Each stage was 3 minutes in duration and the workload was
increased in 30 W increments each stage until 80% of age-predicted $HR_{\text{max}}$ ($HR_{\text{max}} = 220 – \text{Age}$) was reached. Based on the load that elicited 65% of age-predicted $HR_{\text{max}}$, this test was used to calculate the intensity of the following exercise session. The gas exchange of participants was calculated from measurements of oxygen and carbon dioxide concentrations using AMIS 2001 automated metabolic cart (Innovision, Odense, Denmark) and average oxygen uptake was calculated for each stage. This information, coupled with the heart rate during each stage allowed for the prediction of maximal oxygen uptake (13). Participants also completed a familiarization session of the Simon task consisting of 6 blocks of 96 trials (i.e., 3 blocks at rest and 3 blocks while cycling). Each block lasted approximately 3 min 40 s.

**Apparatus and design.**

During the two experimental sessions, participants were required to complete 4 sets of 5 blocks of 96 trials (i.e., 1,920 trials of the Simon task per session). The first set of 480 trials was always completed on the cycle ergometer which faced a computer screen 1 meter away. Two response keys were fixed on the right and left handles of the cycle ergometer. The three remaining sets were carried out while the participant was sitting on a chair 1 meter away from the computer screen for which the participant was provided with hand held response keys. During the exercise session, the first set was carried out after a 5 min warm-up while cycling at 65% age-predicted $HR_{\text{max}}$. The duration of this set was approximately 23 min with approximately 2 min of additional cycling at the end of the set to bring the total cycling time to 30 min for each participant. There was an approximate 90 s ‘cognitive rest’ interval between each block during which participants continued to cycle, and each block of trials was started at an exact 5 min interval. The second set was administered 5 min after exercise cessation, the third set 35 min after exercise cessation and the fourth and final set was administered 65 min after exercise cessation (Figure 1). The same
procedure was followed for the rest session with the exception that during the first set of blocks the participant was seated on the cycle ergometer, but was not cycling. The order of sessions was counterbalanced across participants.

-----------Insert Figure 1 about here-------------------

Simon task.

A white circle, positioned in the centre of the display, remained on the screen throughout the trials acting as a gaze-fixation point for participants. Participants were asked to respond, as quickly and accurately as possible, by pressing the appropriate response key according to the color of a circle delivered either to the left or to the right of the white gaze-fixation circle. The distance from the centre of the fixation circle to the centre of the colored circle located to either the right or left was 7.5 cm. Participants had to respond according to the color of the stimulus while ignoring its spatial location. The mapping of stimulus color to response key was counterbalanced across participants within each age group. The task includes two equiprobable trial types: the congruent trials (CO) during which the spatial location of the stimulus corresponded to the task-relevant aspect of the stimulus (e.g., left stimulus/left response), and the incongruent trials (IN) in which the spatial location of the stimulus corresponded to the opposite spatial location of the response (e.g., left stimulus/right response). As soon as a response key was pressed or when 1.5 s elapsed without a response, the stimulus was removed from the screen and the next trial began.

Data Analysis

The arcsine transformations of the error rate and the mean RT were submitted to separate ANOVA with condition (exercise, rest), period (during exercise, post5, post35 and post65), block (block 1, 2, 3, 4, 5) and congruency (CO, IN) as within-subject factors and age as a between-subjects factor (older vs. younger adults). Post-hoc Newman-Keuls analyses were
conducted on all significant interactions. Significance was set at p < .05 for all analyses. Greenhouse-Geisser degrees of freedom corrections were applied to results. All data are expressed as the mean ± standard error. In addition, RT distribution analyses were used to calculate CAF and delta plots. In each condition and for each age group, RT-distributions (for CO and IN trials separately) were obtained using individual RT-distributions “Vincentized” (26) into 10 equal-size speed bins (deciles). Delta plots were constructed by plotting congruency effect size (IN minus CO) as a function of the response speed (average of means RTs in the CO and IN conditions per decile). Similar to the construction of the delta plots, CAF were obtained using individual accuracy plotted as a function of the response speed per decile. The data presented for both delta plots and CAF are the mean values of each set averaged across participants. ANOVA involving condition, period, congruency and deciles as within-subject factors and age group as a between subjects factor were performed on CAF and delta plots to determine whether curves diverge between rest and exercise conditions and age group.

RESULTS

Reaction Times

Results showed a main effect of age (F(1,22) = 18.34, p <.001, η² = .45) with older adults displaying slower RT (436 ±15 ms) than younger adults (346 ±15 ms) and a main effect of congruency (F(1,22) =269.84, p <.001, η² = .99). Reaction time was significantly slower for IN trials (406 ±11ms) compared to CO trials (377 ±10 ms). The interaction between age and congruency trends towards significance (F(1,22) = 3.69, p =.07, η² = .14) suggesting a larger Simon Effect (SE) for older (32 ±2 ms) than for younger adults (25 ±2 ms). A significant interaction between block and age was observed (F(4,88) = 3.01, p = .04, η² = .12). During the 30 min sets, older adults are more sensitive to the length of the protocol and the repeated exposure to
the cognitive task than young adults. After 15 min of repeated exposure to the task, older adults displayed longer RT. This was significant during the 3rd (7 ms, \( p = .04 \)) and the 4th block (9 ms, \( p < .01 \)) and a trend towards significance for the 5th block (6 ms, \( p = .06 \)) was observed. The interaction between condition and period (\( F(3,66) = 4.75, p = .02, \eta^2 = .18 \)) confirmed that the manipulation of exercise impacted RT performance. Reaction time performance did not change during the rest condition. However, during the exercise condition, participants were faster while cycling and 5 min post-exercise compared to 35 min (\( p < .01 \)) and 65 min (\( p < .01 \)) post-exercise. A closer look at the post-5 period showed that there was a significant difference between the first 2 blocks and the last 2 blocks (\( F(1,23) = 7.75, p = .01, \eta^2 = .25 \)), highlighting a transitory effect of exercise on RT performance (Figure 2). The effect of exercise did not differ between young and old adults (\( F(1,22) = 0.28, p = .60, \eta^2 = .01 \)) and did not interact with any other factor (\( F_s < 1 \)). Collectively, these findings suggest that the facilitating effect observed during exercise persists after cessation for approximately 15 to 20 min but has totally disappeared after 35min for both age groups.

----------Insert Figure 2 about here-------------------

**Decision Error**

Analysis showed that older adults (2.31 ±0.6 %) made fewer errors than younger adults (5.46 ±0.8 %), (\( F(1,22) = 13.15, p < .01, \eta^2 = .37 \)), and a classic effect of congruency illustrating the prevalence of more errors for IN trials (5.05 ±0.8 %) than for CO trials (2.7 ±0.5 %) (\( F(1,22) = 51.22, p < .001, \eta^2 = .95 \)) was observed. The main effect of condition was not significant (\( F(1,22) = 0.26, p = .61, \eta^2 = .01 \)), nor was the interaction with any other factor. This finding suggests that the benefit of exercise is not due to a speed-accuracy tradeoff.
**Between Trials Adjustments**

An ANOVA with condition, period and correctness of the preceding trial (correct vs. error) as within-subject factors and age group as a between-subjects factor was conducted to assess post-error adjustments. Results confirmed the effect of age on RT and showed a post-error slowing effect \( (F(1,21) = 85.87, p < .001, \eta^2 = .80) \), with RT after an error slower (431 ±12 ms) than after a correct trial (388 ±11 ms). The interaction between age and the correctness of the preceding trial \( (F(1,21) = 18.03, p < .001, \eta^2 = .46) \) was also significant, revealing that post-error slowing was larger for older (62 ms) than for younger (23 ms) adults. The interaction between condition and the correctness of the preceding trial was not significant \( (F(1,21) = 0.91, p = .35, \eta^2 = .04) \).

An ANOVA involving condition, time, congruency on trial n (CO vs. IN) and congruency on the preceding trial n-1 (<<CO vs. <<IN) as within-subject factors and age group as a between-subjects factor was conducted to assess the post-conflict adjustment. Results on trial n confirmed the effect of age and the effect of congruency reported in the RT section, and validated the trend previously observed between age and congruency \( (F(1,22) = 4.82, p = .04, \eta^2 = .18) \). The SE is larger for older (29 ms) than for younger adults (22 ms). As expected, the interaction between the congruency on trial n and the congruency on trial n-1 was significant \( (F(1,22) = 23.27, p < .001, \eta^2 = .51) \). Reaction time was slower for CO trials when the preceding trial was IN (393 ±11 ms) compared to when the preceding trial was CO (360 ±9 ms). No other main effect or interaction was significant, suggesting that exercise and age did not affect between-trials adjustments.
Distributional Analysis

Delta plots.

An ANOVA involving condition, period and decile as within-subject factors and age group as a between-subjects factor was conducted on the SE. Results did not reveal a main effect of exercise (F(1,22) = 0.85, p = .37, η² = .04) or any interaction with other factors, which suggests that exercise did not alter cognitive control. Older adults tend to display a larger SE (31 ±2 ms) than younger adults (25 ±2 ms) (F(1,22) = 3.34, p = .08, η² = .13), and the interaction between decile and age (F(9,198) = 5.36, p = .01, η² = .20) confirmed a divergence in the dynamics of the delta plot curves between older and younger adults.

As shown in Figure 3, the gradual and slow negative going slope observed for older adults indicates an efficient cognitive control. The inhibition appears weak initially but strengthens with the lengthening of RT. The SE declines from 35 ms to 6 ms (p < .001) across the distribution. By contrast, the SE did not significantly decline for younger adults (p = .89), the delta curve shows a stronger inhibition at the start and a weaker increase of the suppression as the RT lengthens compared to older adults.

Conditional accuracy functions (CAF).

An ANOVA with condition, period, congruency and decile as within-subject factors and age group as a between-subjects factor was conducted on accuracy rates. In line with the activation-suppression model, the interaction between congruency and decile was significant (F(9, 198) = 51.35, p < .001, η² = .70) and illustrated the strength of the automatic response capture. In the
initial phase (1st decile), the frequency of fast errors is higher for IN trials compared to CO trials (respectively 83 ±1.7 % vs. 99 ±0.3 % of accuracy). This pattern is related to an individual’s susceptibility to produce incorrect responses which are automatically activated by irrelevant information (Figure 4A). Interestingly, the propensity to commit fast errors during CO trials is not different for younger and older adults for the first decile (respectively 98 ±0.4 % vs. 99 ±0.4 %, p = .99). However, younger people have a greater tendency to commit fast errors during IN trials (79 ±2.4 % of accuracy) compared to older people (87 ±2.4 % of accuracy) (p < .001).

The analysis also revealed a trend toward an interaction between exercise, decile and age (F(9, 198) = 2.20, p = .07, η2 = .09) suggesting that exercise differentially impacted the accuracy of performances of younger and older adults (Figure 4B). Younger adults are more prone to increased fast errors during exercise than at rest (respectively 88 ±1.3 % vs. 90 ±1.5 % of accuracy, p < .001). This finding was not observed for older people (p = .40) who are equally accurate during the exercise and rest sessions.

**Time Spent on Task (TOT)**

An ANOVA involving period (i.e., Set1, Set2, Set3, Set4 of both experimental sessions) and decile as within-subject factors and age group as a between-subjects factor was conducted on the SE to assess whether the efficiency of cognitive control is affected by the time spent on task (TOT). If the efficiency of the cognitive control decreases with the TOT, we should observe a divergence in the dynamics of the delta plot curves with the progression of the sets. The delta plots would become less negative as the TOT increased. Results showed that the TOT affected

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3 Considering the results of the distributional analyses reported before, which show that exercise did not alter cognitive control, the ANOVA was conducted on the merged data of the two sessions (exercise and rest).
older adults and younger adults in the same way (F(27, 594) = 0.402, p = .39, η2 = .05). Moreover, a significant interaction between period and decile was observed (F(27, 594) = 3.31, p = .01, η2 = .13) (Figure 5A, left side). Post-hoc analysis revealed that cognitive control is efficient during the 1st Set (SE declined from 34 ms to 4 ms, p < .001) and the 2nd Set (SE declined from 27 ms to 6 ms, p < .001), however, the SE did not decline any more during the 3rd Set (25 ms to 18 ms, p = .12) or the 4th Set (27 ms to 25 ms, p = .76). An ANOVA involving period and decile as within-subject factors and age group as a between-subjects factor was also conducted on accuracy rates, but CAF did not reveal significant main effects or interactions (Figure 5B, right side).

--------Insert Figure 5 about here-------------------

**DISCUSSION**

This study aimed to investigate the influence of an acute bout of moderate intensity exercise on cognitive function and examine the potential lasting improvements over time in older and young adults within the same experimental paradigm over a 2 hour testing period. The study was designed to assess the efficiency of selective control and the propensity to make fast impulsive reactions through the analyses of the percentage of correct responses (CAF) and the magnitude of the interference effect (delta curve) as a function of the latency of the response.

This study illustrates the effectiveness of distributional analyses to quantify the temporal dynamics of information processing and to dissociate the activation of incorrect responses and its subsequent selective suppression. The facilitating effect induced by 30 minutes of cycling at 65% of age-predicted HR\(_{\text{max}}\) exercise was evident for both age groups. The benefit on RT performance persisted 15 to 20 minutes following exercise and disappeared after 35 minutes. Distributional analyses showed that younger people have a higher propensity to commit impulsive errors during
exercise, which was not evident in older adults. Older adults seem to emphasize accuracy of performance and consequently adopt more cautious strategies to complete the task. Despite the larger mean interference effect compared to younger adults, a severe negative going slope of the delta curve over the course of the trials attests to the presence of efficient cognitive control in older people. The suppression mechanisms appear initially weaker for older adults compared to those observed in young adults, but strengthen as the RT gets longer. By contrast, the delta curve pattern for young adults indicates a stronger inhibition at the start with a less pronounced strengthening of the suppression with the lengthening of RT.

The Beneficial Effect of Exercise

Results from this study support the idea that a beneficial influence of exercise on cognitive function can be realized across the lifespan. The magnitude and the duration of the facilitating effect of exercise observed for older adults are similar to those observed in younger adults. These results add further support to recent findings which report beneficial effects of acute moderate exercise on various aspects of cognitive function in older populations (8, 25). Though the exact mechanisms by which acute exercise facilitates cognitive performance are still disputed, an exercise induced increase in brain concentrations of catecholamines (24), which are essential for efficient cognitive function, could modulate the activity of neural networks and explain the transient cognitive changes observed.

Results also suggest that the benefit induced by acute bouts of exercise persists 15 to 20 minutes post-exercise which is less enduring than previously observed with younger adults assessed following 30 minutes of exercise performed at 40% of maximal aerobic power (mean HR about 130 bpm) (15). Moreover, at odds with Davranche & McMorris (9) the present findings showed that the efficiency of cognitive control are not affected by exercise. These discrepancies could be
explained by the intensity and duration of exercise used in the present protocol which was adapted for older adults. Despite the fact that the exercise performed by the older adults is quite challenging, the workload is lighter than those used in previous protocols\(^4\). It is reasonable to presume that exercise intensity, as well as duration, influences the length and the size of the effect on cognitive functioning. Beyond a given intensity threshold, we can assume that exercise can damage cognitive control efficiency as shown by Davranche and collaborators (9). One issue for future research will be to define the optimal parameters for an effective dose-response relationship.

**Effect of Age on Impulse Activation and the Selective Suppression**

It has long been established that older adult’s cognitive performance declines as they age and the literature has consistently found that decrements in processing speeds occur (18). This deficit has been attributed to various age-associated cerebral changes including reduced cerebral blood flow (1) and pre-frontal cortex (PFC) deterioration (35). Consistent with previous studies, results showed that older adults had slower RT, are more accurate and display a larger interference effect compared to younger adults (5, 33, 34). Some researchers have suggested that this larger SE in older adults reflects a greater inhibition cost and less efficient inhibitory processes (4, 20). However, essential information could be lost when behavioral analyses are restricted to mean interference effects.

While older adults displayed a larger interference effect, cognitive control efficiency was not compromised, as illustrated by the negative going slope of the delta curve. The delta curve shows that older adults initially display a weaker suppression mechanism but, as the latency of the response increases, the inhibition strengthens until it exceeds that observed in young adults. It is likely that older adults apply a more cautious response strategy and adopt a greater amount of

\(^4\) For comparison, Davranche & McMorris (2009) used a protocol consisting of 21 minutes of cycling at an intensity corresponding to the individual’s lactate threshold power (i.e., 77% of HRmax).
suppression to direct response activation on the longest RT (5, 27, 39). This interpretation is in line with the results observed on between-trials adjustments and CAF analyses. Post-error adjustments showed that the post-error slowing is more than twice as large for older compared to young adults. The analyses of the percentage of correct responses indicated that older adults committed a significantly lower proportion of fast impulsive errors (Figure 4A). Indeed, older adults seem to adopt a more cautious strategy, especially when the risk to commit an error is elevated. In contrast, young people display a higher propensity to commit impulsive errors and this predisposition is also evident during exercise (Figure 4B). Considering these findings, it appears that the older participants did not show less control than the younger ones. It seems likely that the differences observed between young and old adults, in the current study, are mostly due to differences in speed-accuracy strategy selection.

Several authors have shown that the propensity to make fast impulsive errors and the strength of response inhibition are sensitive to speed or accuracy instructions (2, 38). Under speed instructions, subjects commit more impulsive errors on conflict trials compared to instructions stressing accuracy. The amount of time available is not sufficient to build up the suppression mechanisms necessary to counteract the strong initial impulse activated by irrelevant information. This pattern is similar to that observed in the present study with young adults. Older people, conversely, appear to be more concerned with the accuracy of performances than about the speed of responses. If this interpretation is accurate, we would expect that, at equivalent accuracy rates, older adults could be able to manage response conflict as efficiently as young adults. These findings highlight the need to take into account, in future studies, the speed-accuracy level in order to disentangle the effect of strategy from the effect of aging.

The implicit activation of age-related stereotypes related to the design of the protocol may account, at least in part, for the strategy adopted by older adults. Before taking part in the
experiment, participants were told that both young and old adults would be involved in the protocol. Due to the perceived implicit threat of being judged stereotypically, this apparently trivial information has been shown to affect performance and exacerbate age-related stereotypes which predict poorer RT performances (12). Future research needs to neutralize the threat of implicitly activated negative age-related stereotypes through specific instructions. According to Mazerolle et al. (22), an efficient way to make the aging stereotype irrelevant for the testing situation is to inform participants that performance on the present cognitive task usually does not differ between younger and older adults (age neutral).

**Time Spent on Task (TOT)**

In this protocol, the time spent on task was substantial and distributional analyses revealed that the efficiency of the suppression mechanisms was not maintained for the duration of the experimental sessions. The impairment of cognitive control was evident after 1 hour and is likely explained by an increase in mental fatigue as time progressed (31). Interestingly, the pattern of the delta curves (Figure 5A), is very similar to those reported by Wylie and collaborators with Parkinson’s disease patients, divided into subgroups as a function of the severity of their motor symptoms (37). In both cases, the negative going slope of the delta curve suggests a less proficient suppression of incorrect response activation with the increasing of the motor symptom's severity or with the increase of the cognitive fatigue over time.

This is the first study to comprehensively examine the role of acute moderate exercise on cognitive control in older adults while concurrently examining the post exercise maintenance of cognitive improvement. Results highlighted the effectiveness of distributional analysis to examine the temporal dynamics of conflict resolution, and support the idea that a beneficial influence of exercise on cognitive performance can be realized across the lifespan.
The population aging, we are currently experiencing, demands a concentrated effort to explore methods of combating age-associated cognitive decline. Researchers should primarily focus efforts on defining the optimal parameters for an effective dose-response relationship with regards to exercise and cognitive performance benefits. By closely examining the cognitive consequences of acute bouts of exercise and the post-exercise duration over which benefits may be noticed, we take one step closer to understanding any link between acute exercise effects and chronic adaptations which lead to cognitive health benefits. Of particular interest is the cognitive facilitation observed post-exercise. Research examining the effects of acute exercise on cognitive performance and the duration over which any changes might be observed is as an initial step in the process to strengthening exercise intervention prescriptions. Valuable information can be gathered in relation to the duration and intensity of exercise which facilitates cognitive function. The next step for researchers is to investigate the impact of repeated exposure to acute bouts of exercise, and examine any aggregate cognitive benefit which may appear as a result of accumulating exercise sessions. This focus is necessary to establish when in the process of chronic exercise participation cognitive gains manifest.

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Figure 1. Schematic representation of the design of the protocol.

Figure 2. Mean reaction time in milliseconds for rest (empty circles) and exercise (full circles) conditions, over the four testing periods (on the bicycle, post5, post35 and post65) and across the 5 blocks of the Simon task.

Figure 3. Delta plot of reaction time, for young (white circles) and old (black triangles) adults, illustrating the magnitude of the Simon effect (in milliseconds) as function of reaction time deciles. Mean reaction time (in milliseconds) corresponding to each reaction time deciles is reported on x-axis for a better comparison of both age groups.

Figure 4. Conditional accuracy functions (CAF) representing (A) the percentage of accuracy for compatible trials (CO, full symbols) and incompatible trials (IN, empty symbols) as function of reaction time for young (circles) and old (triangles) adults; and (B) the percentage of accuracy during exercise (full symbols) and rest (empty symbols) conditions as function of reaction time for young (circles) and old (triangles) adults.

Figure 5. (A) Delta plot of reaction time illustrating the magnitude of the Simon effect (in milliseconds) as function of mean reaction time for the 1st Set (diamond), the 2nd Set (circle), the 3rd Set (triangle), and the 4th Set (square). (B) Conditional accuracy function (CAF), over the four testing periods, as function of mean reaction time.
Figure 2

![Graph showing mean RT (ms) across blocks during exercise and rest conditions.]
Figure 5

A

B

Mean RT (ms)

Simon effect (ms)

Accuracy (%)

Mean RT (ms)
Table 1. Participants’ anthropometrical and physiological characteristics.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean (SD)</th>
<th>All</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Size</td>
<td></td>
<td>Young</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Old</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Age (years)</td>
<td></td>
<td>Young</td>
<td>23 (2)</td>
<td>24 (1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Old</td>
<td>63 (2)</td>
<td>62 (1)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td></td>
<td>Young</td>
<td>172 (10)</td>
<td>167.3 (5.9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Old</td>
<td>171.6 (6.7)</td>
<td>167.8 (1.8)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td></td>
<td>Young</td>
<td>63.1 (10.3)</td>
<td>58.6 (6.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Old</td>
<td>83.1 (11.8)</td>
<td>78.6 (8.5)</td>
</tr>
<tr>
<td>Pred. HR(_{\text{max}}) (bpm)</td>
<td></td>
<td>Young</td>
<td>157 (2.6)</td>
<td>158 (1.47)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Old</td>
<td>197 (2.02)</td>
<td>196 (1.17)</td>
</tr>
<tr>
<td>Exercise HR (bpm)</td>
<td></td>
<td>Young</td>
<td>123 (1.46)</td>
<td>123 (1.62)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Old</td>
<td>102 (4.7)</td>
<td>104 (4.19)</td>
</tr>
<tr>
<td>Exercise HR (% of HR(_{\text{max}}))</td>
<td></td>
<td>Young</td>
<td>62 (1)</td>
<td>63 (1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Old</td>
<td>65 (3)</td>
<td>66 (3)</td>
</tr>
<tr>
<td>Rest HR (bpm)</td>
<td></td>
<td>Young</td>
<td>76 (6.8)</td>
<td>77 (6.45)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Old</td>
<td>68 (7.81)</td>
<td>69 (7.38)</td>
</tr>
<tr>
<td>Pred. (\text{VO}_{2\text{max}}) (ml/kg/min)</td>
<td></td>
<td>Young</td>
<td>33.2 (9.8)</td>
<td>29.7 (7.4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Old</td>
<td>23.3 (6.8)</td>
<td>19 (4.3)</td>
</tr>
</tbody>
</table>

Note: Pred. HR\(_{\text{max}}\) = predicted maximal heart rate, HR = heart rate, bpm = beats per minute, Pred. \(\text{VO}_{2\text{max}}\) = predicted maximal oxygen uptake