Does Acute Exercise Switch Off Switch Costs? A Study With Younger and Older Athletes

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This study investigated the effects of acute exercise on 53 young (16–24 years) and 47 older (65–74 years) adults’ switch-task performance. Participants practiced sports requiring either low or high cognitive demands. Both at rest and during aerobic exercise, the participants performed two reaction time tasks that differed in the amount of executive control involved in switching between global and local target features of visual compound stimuli. Switch costs were computed as reaction time differences between switch and nonswitch trials. In the low demanding task, switch costs were sensitive only to age, whereas in the high demanding task, they were sensitive to acute exercise, age, and sport-related cognitive expertise. The results suggest that acute exercise enhances cognitive flexibility and facilitates complex switch-task performance. Both young age and habitual practice of cognitively challenging sports are associated with smaller switch costs, but neither age nor cognitive expertise seem to moderate the relationship between acute exercise and switch-task performance.

Keywords: executive function, physical activity, aging, expertise, orienteering, soccer

A rapidly growing body of literature has focused on the effects of acute bouts of physical exercise on cognition (for reviews, see Brisswalter, Collardeau, & Arcelin, 2002; Tomporowski, 2003; Lambourne & Tomporowski, 2010). In the last decade, the interest has progressively focused on the relationship between physical exercise and higher-order cognitive functions, such as executive functions (Etner & Chang, 2009). It is widely accepted that executive functions involve a frontoparietal network and include such functions as planning, scheduling, working memory, and inhibition, which contribute to cognitive flexibility and the successful regulation of thoughts and actions. Such broad range of functions, reflecting the nonunitary nature of the executive (Miyake et al. 2000), has fostered the use of a great variety of psychometric and neuropsychological tasks to assess the impact of

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physical exercise on executive function. As a consequence, the research outcomes are not readily comparable.

When acute bouts of exercise are antecedent to cognitive task performance (i.e., off-task research), there is consistent evidence of positive aftereffects obtained with various tests of executive function (e.g., Hogervorst, Riedel, Jeukendrup, & Jolles, 1996; Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009). Only a few studies failed to detect any exercise effects in young adults employing a task-shifting paradigm (Coles & Tomporowski, 2008; Tomporowski & Ganio, 2006), and to our knowledge, no evidence of detrimental aftereffects exists. With respect to the effects of acute exercise on a concomitant cognitive task (i.e., in-task research), there is inconsistency among studies, with evidence showing executive task performance being impaired, improved, or unaffected by concomitant exercise. Dietrich and Sparling (2004) attributed exercise-induced decrements in performance to transient impairment of brain structures that subtend higher-order cognitive functions, which are sensitive to strains on metabolic resources under physical effort (i.e., exercise-induced transient hypofrontality hypothesis) (Dietrich, 2006). In contrast, Pesce, Capranica, Tessitore, and Figura (2003) observed reaction time facilitation on tasks challenging executive attention and interpreted it in terms of an increased amount of allocatable resources under submaximal physical effort. Recent research has provided support for both interpretations. Results obtained by Pontifex and Hillman (2007) and Del Giorno, Hall, O’Leary, Bixby, and Miller (2010) supported the hypofrontality hypothesis. Other authors reported either no effect (Davranche, Hall, & McMorris, 2009) or an improvement (Joyce, Graydon, McMorris, & Davranche, 2009) of executive task performances, or a complex pattern of exercise-induced deterioration of some executive functions and maintenance of the full efficiency of other executive functions (Davranche & McMorris, 2009). Studies designed to measure the time course of exercise-induced effects by integrating both in-task and off-task measurements showed either an impairment of executive performance during exercise persisting immediately following exercise in the case of high exercise intensity (Del Giorno et al., 2010), or no impact of exercise (Lambourne, Audiffren, & Tomporowski, 2010), or changes interpreted as shifts in task performance strategy (Audiffren, Tomporowski, & Zagrodnik, 2009).

Relatively few studies have investigated the effects of acute exercise bouts on older adults’ performance ofexecutively challenging tasks (e.g., Kamijo, Hayashi, Yahiro, Tanaka, & Nishihira, 2009; Netz, Argov, & Inbar, 2009; Pesce, Cereatti, Casella, Baldari, & Capranica, 2007; Pesce, Cereatti, Forte, Crova, & Casella, 2011). Researchers using off-task study designs have reported beneficial effects for older adults (e.g., Kamijo et al., 2009; Netz et al., 2009), but not all studies have (Barella, Etnier, & Chang, 2010). Studies employing in-task designs showed that the benefits of acute exercise were accounted for by physical fitness or prolonged practice of endurance sports (Netz et al., 2009; Pesce et al., 2011).

The habitual participation in sports training, however, cannot be merely conceived in terms of physical fitness outcomes, since different sports may differ greatly in their demands on cognitive skills. Extensive sport practice seems to be associated to superior performance not only in sport-specific cognition, as evidenced in the “expert performance approach” (e.g., Williams & Ericcson, 2005), but also in fundamental cognitive skills and general processing speed, as assessed within the “cognitive component skills approach” (Voss, Kramer, Basak, Prakash,
However, the type of sport clearly moderates this relationship (Mann, Williams, Ward, & Janelle, 2007): expert open skill athletes, for instance, are characterized by attentional flexibility enabling them to minimize attentional costs when coping with unpredictable opponent behaviors (e.g., Nougier & Rossi, 1999).

Cognitive expertise acquired practicing sport seems to be a moderator of the relationship between acute exercise and cognition (e.g., Cereatti, Casella, Manganeli, & Pesce, 2009; Pesce, Cereatti et al., 2007). While an exercise-induced general facilitation of reaction time (RT) performances may be accounted for by increments in arousal and in the amount of allocatable resources (e.g., Brisswalter et al., 2002), differences in acute exercise effects between individuals with or without sport-related cognitive expertise may depend on the fact that experienced athletes are better able to efficiently allocate the freed resources to ongoing cognitive tasks (Pesce, 2009). However, there is a lack of research investigating whether the relationship between an acute bout of exercise and a concomitant executive task performance is moderated by individual differences in age and cognitive expertise.

The aim of the current study was to assess whether aerobic in-task exercise affects cognitive flexibility and whether this relationship is moderated by age and cognitive expertise deriving from chronic practice of cognitively challenging sports. To this aim, we chose a classical index of cognitive flexibility and executive control of cognitive processes, labeled specific (or local) switch cost (Rogers & Monsell, 1995). In tasks involving the switching between two tasks A and B, trial \( n + 1 \) may be a repetition of task A or B (A-A or B-B) or an alternation of tasks A and B (A-B or B-A). In these tasks, specific switch costs are computed as the difference between the mean RT for repetition trials and the mean RT for switch trials within heterogeneous trial blocks. This switch cost is supposed to index the duration of an executive control process that, in switch trials, must activate a new relevant task set, suppressing the proactive interference from the previous stimulus-response mapping for the task that was, but is no longer, appropriate. It has been also argued that in standard task switching paradigms using external cues to inform participants which task is currently required, the switch cost could merely reflect passive mechanisms, such as priming, that facilitate performance when the task or elements of the task are repeated (Logan & Bundesen, 2003). However, electrophysiological studies provided evidence against this view, confirming that explicitly cued task switching elicits a true executive control process of task set reconfiguration (e.g., Jost, Mayr, & Rösler, 2008). In the current study, we analyzed a RT cost generated by explicitly cued switches between global and local target features of complex visual stimuli. The switch cost computation isolates the cognitive flexibility requirements of the attentional task from nonexecutive processes of perceiving and responding. We expected an arousing beneficial effect of in-task exercise on cognitive flexibility indexed by the switch costs.

We also addressed the influence of age and sport-related cognitive expertise on cognitive flexibility as well as their role as potential moderators of the relationship between acute exercise and cognitive flexibility. According to most evidence, we expected no age effects on the employed local switch cost measure of cognitive flexibility (Wasylyshyn, Verhaeghen, & Sliwinski, 2011), but we hypothesized that aging would negatively influence the relationship between acute exercise and cognitive flexibility, due to age-related increments in dual task interference (Verhaeghen & Cerella, 2002). In contrast, we expected that the extensive practice of
cognitively challenging sports would be associated with overall reduced switch costs. In strategic team sports such as soccer, requiring attention sharing between an object in the environment and the diverse arrays of teammates and opponents (Mann et al., 2007), the flexibility of attention enables expert athletes to minimize the effects of unexpected events, efficiently disengaging attention from misleading information such as that delivered by feinting opponents (Nougier & Rossi, 1999). In strategic individual sports such as orienteering, requiring the ability to solve complex multitasking problems (Eccles, 2008), attentional and cognitive flexibility enables participants to cope with the need to switch quickly between the tasks of attending to the map, the environment, and the travel (Eccles, Walsh, & Ingledew, 2006). Therefore, switch costs should be reduced in expert soccer players and orienteers, who should be better able to overcome the perseverative tendency to maintain the last attended task-set configuration. In addition, we hypothesized that expertise would act as a positive moderator of the relationship between acute exercise and cognitive flexibility, causing a more pronounced reduction of switch costs during physical exercise. In fact, both soccer players and orienteers, in their field practice, routinely perform cognitively challenging tasks while engaged in effortful physical tasks and, therefore, seem to be able to allocate available resources during acute exercise more efficiently than nonathletes (Pesce, Tessitore, Casella, Pirritano, & Capranica, 2007; Cereatti et al., 2009).

**Methods**

**Participants**

One hundred male and female participants, aged 16–24 years ($n = 53$) and 65–74 years ($n = 47$), volunteered to take part in the study after institutional approval of the protocol. According to the criteria for inclusion, data of 85 participants were drawn from samples used by Pesce et al. (Cereatti et al., 2009; Pesce et al., 2003; Pesce, Cereatti et al., 2007; Pesce, Tessitore, et al., 2007; Pesce et al., 2011) to analyze acute exercise effects on visual attentional focusing. The specific switch cost index used in the current study reflects sequence effects that were not analyzed in the previous series of studies. The data of 15 other participants (older soccer players) were added to balance the composition of the subgroups of young and old athletes practicing sports requiring high cognitive flexibility.

All participants provided written informed consent. For participants under age 18, also parents’ written consent was requested. Participants lived fully independent lifestyles and had no evidence or history of neuromuscular disorders, cognitive impairment, or use of medications that would affect the test performance, as assessed by means of the AAHPERD exercise/medical history questionnaire. Both groups of younger and older participants were physically active and had a stable pattern of physical activity during a period of at least 3 years. They were subdivided into two gender-matched subgroups each as a function of whether they were practicing sports with low cognitive demands (i.e., swimming, gymnastics, running, rowing) at a noncompetitive level (26 younger and 22 older individuals) or were club-standard or elite athletes practicing sports with high demands on cognitive flexibility (i.e., orienteering, soccer; Eccles, 2008; Mann et al., 2007) at
a competitive level (27 younger and 25 older individuals). The criterion for inclusion in the subgroup of club-standard or elite competitive athletes was having at least 5–10 years of experience.

**Apparatus and Stimuli**

Participants were seated on a cycle ergometer in a dimly lit room at a distance of 60 cm from a PC-driven video screen. Four visual displays were used: the instruction, presented on the screen only one time at the beginning of the experimental session, and three types of stimuli, sequentially presented on the screen at each trial. The three types consisted of a central fixation point, a spatial cue of variable size, and a compound stimulus. The fixation point was a tilted “T” of 0.4° × 0.4°, and the spatial cue was an empty box of 1° × 1° or 5° × 5°. The compound stimulus was a large letter (4.6° × 4.6°) made of 13–17 small letters (0.6° × 0.6°) spaced 0.4° in a 5 × 5 matrix. The large letter and its small elements represented the global and local level of the compound stimulus, respectively. The large letter could be an A, E, F, or H; the small elements were the remaining letters. The fixation point, the large box, and the following compound stimulus were centered on the screen; the small box could randomly appear at one of the locations of the elements composing the compound stimulus.

**The Attentional Task**

Each trial consisted of the sequence of events represented in Figure 1. In five sixths of the trials (go trials), the compound stimulus contained a target letter (e.g., “H,” Figures 2–3) either at the global or at the local level. Participants had to react as soon as possible to it by pressing a RT-key with the right index finger while gazing at the fixation point. In the remaining trials (no-go trials), the compound stimulus did not contain the target letter and participants had to refrain from responding.

Two versions of the attentional task were performed, differing in the amount of executive attention control required (see below for the distinguishing features of the two tasks). Each version consisted of two blocks of 76 trials, one with short (150 ms) cue–target stimulus-onset asynchrony (SOA) and one with long (500 ms) SOA. Each block included four warm-up trials, 60 go trials, and 12 no-go trials. Testing was preceded by one block of practice trials to ensure that set acquisition reached a learning asymptote in both younger and older individuals. The minimum amount of practice (40 trials) could be automatically prolonged until a criterion frequency of 80% correct responses was reached. However, no participants needed prolonged training. The order of the two versions of the task and of the two blocks of trials with short and long SOA within each task was counterbalanced across participants. Cue sizes and target levels were balanced and randomized within blocks. Each of the two blocks of experimental trials lasted 3–4 min depending on SOA and reaction speed of the participant. Both attentional tasks, including practice and real experimental blocks, were performed at rest and during submaximal intensity exercise in counterbalanced order in two sessions on different days. The testing took place off season, either in the morning or in the afternoon, according to athletes’ availability, avoiding the time before 9 a.m., between 1 and 3 p.m., and after 7 p.m. The same time of day was maintained in the resting and workload session.
Low Demanding Task. In 80% of the go trials, the size of the cue and that of the upcoming target were matched: a large cue was followed by a global target (Figure 2, panel a, right) and a small cue by a local target at the same location (Figure 2, panel a, left). As is common in spatial cueing paradigms, in the remaining 20% of trials, cue and target size were mismatched.

High Demanding Task. In 80% of the go trials, cue and target size were mismatched: a large cue was followed by a local target at its center (Figure 3, panel a, left) and a small cue by a global target centered on the screen (Figure 3, panel a, right), while only in the remaining cases (20%), the target letter matched cue size and location.

The two versions of the RT task required space-based and object-based components of attention, operationalized by means of the effects of advance spatial cues and of global- or local-level targets, respectively. The two versions differed in the amount of top-down executive control required to cope with the space-based attention demands. The “low demanding” version initially requires voluntary attention but becomes automated with practice. The “high demanding” task, in contrast, requires a tonic level of top-down executive control because cue and target are mismatched on most of the trials and intentional control is continuously required to suppress the automatic allocation of spatial attention on the cued area and to focus attention based on the expectation of an upcoming target at a different spatial scale.
Figure 2 — Schematic representation of the four types of switch and nonswitch trials in the low demanding task. As an example, the target letter is “H.”

Switch Cost Computation

Equally frequent trials with global or local target stimulus dimensions were presented in a random order within heterogeneous blocks. Specific switch costs were calculated as the time required to switch from attending to the global level of a visual object on trial \( n \) to attending to the local level on trial \( n + 1 \) (or vice versa). Trials with response errors (responses with RTs shorter than 200 ms or longer than 2,500 ms) were discarded. Trials with cue–target matching in the low demanding task (Figure 2) and those with cue–target mismatching in the high demanding task (Figure 3) were analyzed.

Each trial was coded as “switch trial” or “nonswitch trial” according to whether it was preceded by a trial with a target at the different or the same object level, respectively. Thus, four types of trials were identified: (1) switch to global (STG, i.e., a global target trial preceded by a local target trial, Figures 2–3, panel a); (2) nonswitch global (NSG, i.e., a global target trial preceded by a global target trial,
Figures 2–3, panel b); (3) switch to local (STL, i.e., a local target trial preceded by a global target trial, Figures 2–3, panel c); (4) nonswitch local (NSL, i.e., a local target trial preceded by a local target trial, Figures 2–3, panel d). Median RTs were computed separately for each type of trial. Switch costs were computed as RT differences between switch trials and nonswitch trials as a function of switch direction: (1) local-to-global switch cost = RT_{STG} – RT_{NSG} (Figures 2–3, panels a and b); (2) global-to-local switch cost = RT_{STL} – RT_{NSL} (Figures 2–3, panels c and d).

The Acute Physical Exercise Condition

Exercise consisted of cycling on a cycle ergometer at 50–60 revolutions per minute (rpm). Individual workloads corresponding to a target hearth rate (THR) of 60% heart rate reserve (HRR) were previously computed for each participant. Percentage of HRR was chosen to ensure a similar relative increase in exercise intensity above rest for participants whose fitness level could differ due to age and sport practice.
In fact, resting HR is 0% of HRR for less-fit as well as for more-fit participants, and an exercise intensity of given percentage of HRR represents a fixed relative increase above rest independently of fitness level (Swain, 2000). The intensity corresponding to 60% HHR was chosen to maintain aerobic exercise throughout the attentional test and to avoid exceeding the anaerobic threshold.

The exercise session lasted between 20 and 24 min. Participants warmed up to their individual THR via an incremental protocol consisting of 2-min steps with a load increment of 50 W, starting at 50 W. Then they maintained their THR for about 10 min during which they read task instructions and listened to explanations by the experimenter. Next, the attentional task was started while the participant continued to exercise. Heart rate was monitored and the individual workload adjusted in the case of deviations from THR (± 5 beats per minute [bpm]). Participants had a 1-min resting period between each block, which was followed by pedaling to return to their individual THR before starting the next block.

Preliminary Analyses

Before performing the main analyses to evaluate exercise effects on switch costs, preliminary analyses were run to examine (1) if the expected RT difference between switch and nonswitch trials varied under different attentional control conditions and (2) if there were age and acute exercise effects on RTs and response errors. The only study paradigm most similar to that used by Pesce and coworkers (2003) and in the current study—coupling global/local target stimulus dimensions and spatial cueing with different demands on top-down control (Lamb, Pond, & Zahir, 2000)—was not targeted to study switch costs. Thus, this interplay had to be examined before searching for exercise effects on switch costs. Moreover, since switch costs are RT-differences, their hypothesized reduction during physical exercise would be meaningless if it would be paralleled by an opposite increment in absolute RT. Conversely, if shorter RTs and switch costs during exercise would be paralleled by higher rates of responses to no-go trials, it should be just due to the fact that accuracy was traded for speed. Thus, we ran preliminary analyses on both errors and RTs. Three types of error percentages were separately calculated for younger and older individuals, both at rest and during exercise: real response errors (responses to no-go trials), anticipated responses (RTs shorter than 200 ms), and delayed responses (RTs longer than 2,500 ms). Because anticipated responses were overall very low (0.2%), they were not analyzed further. The proportions of response errors and delayed responses were transformed to logits and submitted to separate mixed ANOVA models, both for the low and the high demanding tasks, with age class (16–24 vs. 65–74 year-old) and physical exercise (rest vs. aerobic exercise) as factors. For response errors, there was only a nonsignificant tendency toward higher error rates during exercise than at rest both in the low demanding task (9.5% vs. 8.5%, $p = .101$) and in the high demanding task (7.3% vs. 8.3%, $p = .139$). This indicates that a shift in speed–accuracy trade-off set point, if given, cannot entirely explain facilitating effect of exercise on RT. For delayed responses, a highly significant age effect emerged both in the low demanding task, $F(1, 98) = 79.19, p < .001, \eta_p^2 = .45$, and in the high demanding task, $F(1, 98) = 82.59, p < .001, \eta_p^2 = .46$, with higher percentages of delayed responses for older than younger individuals (7.5% vs. 0.9% and 5.7% vs. 0.9%, respectively).
A 2 × 2 × 2 × 2 mixed-model ANOVA was run on RTs, separately for the low and high demanding tasks, with age class (16–24 vs. 65–74 year-old) as a between-participants factor and physical exercise (rest vs. aerobic exercise), type of trial (switch vs. nonswitch trials), and target level (global vs. local) as within-participants factors. Post hoc analyses were performed by means of pairwise comparisons (t test) and alpha level was adjusted for multiple comparisons (Bonferroni technique, adjusted \( p = .025 \)). Main effects for age and exercise emerged in both tasks. Reaction time was faster for younger than for older individuals (low demanding task: 467 vs. 702 ms, \( F[1, 98] = 108.83, p < .001, \eta_p^2 = .53 \); high demanding task: 507 vs. 636 ms, \( F[1, 98] = 61.08, p < .001, \eta_p^2 = .38 \)) and during exercise than at rest (low demanding task: 558 vs. 597 ms, \( F[1, 98] = 21.18, p < .001, \eta_p^2 = .18 \); high demanding task: 539 vs. 597 ms, \( F[1, 98] = 44.38, p < .001, \eta_p^2 = .31 \)). In addition, a significant interaction between type of trial and target level emerged for both tasks (low demanding task: \( F[1, 98] = 29.21, p < .001, \eta_p^2 = .23 \); high demanding task: \( F[1, 98] = 64.53, p < .001, \eta_p^2 = .40 \)).

The expected result of longer RTs on switch trials as compared with nonswitch trials, leading to positive switch cost values, was found for global targets in the low demanding task (Table 1, left top) and for local targets in the high demanding task (Table 1, right bottom). However, negative switch cost values emerged for local targets in the low demanding task (Table 1, left bottom) and for global targets in the high demanding task (Table 1, right top). In both cases, the nonswitch trials were the second of two consecutive trials with small cue (Figure 2, panel d, and Figure 3, panel b). The strong automatic narrowing of spatial attention elicited by small cues probably outweighed the persistence of attention on the last attended object level (i.e., level repetition effect), particularly when the task-relevant object level was global. This hypothesis is supported by the evidence that object-based effects are obtained under conditions of spread attention, whereas they are reduced under conditions of narrow attention (Goldsmith & Yeari, 2003).

### Table 1  Means ± SD of Median Reaction Times (in Milliseconds) Calculated for the Four Types of Trials Used for Switch Cost Computation

<table>
<thead>
<tr>
<th>Type of Trial</th>
<th>Low Demanding</th>
<th>High Demanding</th>
</tr>
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<tbody>
<tr>
<td>Switch to global (STG)</td>
<td>538 ± 129</td>
<td>535 ± 92</td>
</tr>
<tr>
<td>Nonswitch global (NSG)</td>
<td>494 ± 103</td>
<td>604 ± 141</td>
</tr>
<tr>
<td>Switch to local (STL)</td>
<td>635 ± 243</td>
<td>597 ± 136</td>
</tr>
<tr>
<td>Nonswitch local (NSL)</td>
<td>643 ± 243</td>
<td>535 ± 85</td>
</tr>
</tbody>
</table>

Note: Data are collapsed across resting and exercise conditions.
Results

In the preliminary analyses, an interaction between space-based and object-based components of visual attention suggested a bias in two of the four types of switch costs. Consequently, only the two unbiased switch costs were submitted to main analyses: local-to-global switch costs in the low demanding task and global-to-local switch costs in the high demanding task. Switch costs were analyzed via a $2 \times 2$ mixed-model ANOVA, separately for the low and high demanding tasks. The between-participants factors were age class (16–24 vs. 65–74 years old) and type of sport practiced (cognitively high vs. low demanding); the within-participants factor was acute physical exercise (rest vs. aerobic exercise). Main effects were evaluated to test for the influence of acute exercise, age, and sport-related expertise on switch costs. Interactions between acute exercise and age or expertise were evaluated to test for moderation, that is, to test whether age and expertise moderate the relationship between acute exercise and switch task performance.

Low Demanding Task

Evaluation of local-to-global switch costs indicated that there were no effects for physical exercise ($p = .688$) or sport-related cognitive expertise ($p = .562$). A significant main effect emerged for age, $F(1, 96) = 18.52, p < .001, \eta_p^2 = .16$, with larger switch costs for older than younger individuals (Figure 4a, left).

High Demanding Task

Evaluation of global-to-local switch costs revealed main effects for physical exercise, $F(1, 96) = 4.63, p = .034, \eta_p^2 = .05$; age, $F(1, 96) = 13.82, p < .001, \eta_p^2 = .13$; and sport-related cognitive expertise, $F(1, 96) = 4.85, p = .030, \eta_p^2 = .05$. Switch costs were significantly smaller during exercise than at rest (Figure 5, right), they were smaller in younger than in older individuals (Figure 4a, right), and were they smaller in athletes practicing cognitively challenging sports compared with individuals practicing low demanding sports (Figure 4b, right). We observed neither significant Physical Exercise $\times$ Age nor Physical Exercise $\times$ Cognitive Expertise interactions ($p = .34$ and $.56$, respectively).

Discussion

The aim of the current study was to assess whether aerobic in-task exercise affects cognitive flexibility and whether the relationship is moderated by age and cognitive expertise deriving from chronic practice of cognitively challenging sports. The results support the hypothesis of an exercise-induced facilitation of cognitive flexibility, as revealed by reduced switch costs during acute exercise. In addition, age and sport-related cognitive expertise seem to be responsible for individual differences in cognitive flexibility, but neither age nor cognitive expertise seem to moderate the relationship between acute exercise and cognitive flexibility.
Figure 4 — Switch costs (±SD) in the low and high demanding task as a function of (a) age and (b) individual differences in cognitive expertise acquired through extensive sports practice. *p < .05.
The results also suggest that the amount of executive control involved in the cognitive task influences the relationship between acute exercise and cognitive flexibility because beneficial exercise effects emerged only when the switch task involved the effortful maintenance of a high amount of executive control. In our switch task, executive control was needed when the task-relevant object level (global or local) changed, but its amount also varied as a function of the valid or misleading information delivered by the advance spatial cue. The presence of beneficial exercise effects only in the more challenging task with most frequent misleading cues (Figure 5, right) is a novel result and differs from previous acute in-task exercise research (Davranche et al., 2009).

The hypothesis that individual differences in age and chronic practice of sports with high cognitive demands would moderate the relationship between acute exercise and performance on a task requiring cognitive flexibility was not confirmed. The results differ from those reported in previous studies using the same attentional RT task, but not analyzing the switch cost index of cognitive flexibility (Pesce, Tes-sitore, et al., 2007; Cereatti et al., 2009). The earlier studies suggested that young orienteers and soccer players could better exploit available mental resources during physical exercise to speed up RT performance because of their acquired skills. Further research is needed to determine whether the impact of cognitive expertise depends on measures that tap executive or nonexecutive functions.

Figure 5 — Switch costs (±SD) in the low and high demanding task as a function of the presence or absence of a concomitant aerobic exercise bout. *p < .05.
Regardless of acute exercise, there are differences in switch costs as a function of age and sport-related cognitive expertise. Even though aging seems to deteriorate cognitive flexibility, the habitual practice of cognitively challenging sports seems to enhance it. The positive effect of expertise is in line with the hypothesis, whereas the negative effect of aging, in contrast with the hypothesis, supports the findings of a minority of studies (Kray & Lindenberger, 2000; Meiran, Gotler, & Perlman, 2001). Older adults, as compared with their younger counterparts, showed generalized reductions in cognitive flexibility when performing both low and high demanding tasks (Figure 4a), probably owing to their lower ability to recruit resources in a flexible manner. In contrast, athletes practicing cognitively demanding sports showed a cognitive advantage, as compared with other sportsmen, only when faced with the more complex task (Figure 4b, right).

The beneficial effect of expertise in cognitively challenging sports and the effect of acute exercise emerged only in the more demanding attentional task. This finding may be explained in terms of cognitive effort and its role in determining the allocation of available resources during an ongoing cognitive task (e.g., Sanders, 1983). The higher amount of cognitive effort required to cope with the more demanding task may have led to optimal allocation of the resources freed during the acute exercise bout (Pesce, 2009). As regards the expertise effects, assuming that perceived task complexity and, consequently, cognitive effort vary with the individual level of cognitive expertise, it can be argued that soccer players and orienteers better exploit their superior cognitive skills in the task that was sufficiently challenging for them to develop optimal levels of cognitive effort (e.g., Pesce, Tessitore, et al., 2007). When the executive demands of the cognitive task were less challenging, it is probable that individuals both practicing and those nonpracticing sports with high cognitive demands performed close to their ceiling without high levels of cognitive effort.

The present study employed a laboratory-based indicator of cognitive flexibility to assess the role of expertise acquired through the prolonged practice of cognitively demanding sports. The observation that switch costs are reduced in athletes who extensively practice strategic sports supports the hypothesis that extensive sport practice results in superior cognitive skills that are transferable to different task environments (Voss et al., 2010). From both sport-specific and sport-general perspectives, the primary characteristics of the cognitive expertise levels of athletes who practice strategic sports is seen in unpredictable complex situations that lack regularity and require rapid information processing (Mann et al., 2007). A strategy adopted by expert athletes that has received empirical support is to “expect the unexpected.” This strategy appears to minimize the orienting costs when visual attention has to be disengaged from an erroneously attended location in the visual field (Nougier & Rossi, 1999). The low switch costs of expert athletes found in the current study support the “cost minimization” hypothesis proposed by Nougier and coworkers (e.g., Nougier & Rossi, 1999) and extends it from the specific control of visuospatial attention to the more general executive control for task-set reconfiguration.

Conclusions can be drawn from both a general and an applied cognitive psychology perspective. The fact that the practice of strategic sports is associated with enhanced cognitive flexibility during a laboratory-based, sport-unspecific test
confirms that the domain of sport offers cognitive researchers a natural laboratory in which to study cognitive functioning and to capture the nature of cognitive expertise. In addition, the presence of beneficial effects of sport expertise in both young and old adulthood supports the view that senior participation in strategic sports contributes to determine successful cognitive aging (Spirduso et al., 2005). The observed facilitating effect of acute exercise on task switching performance has applied relevance. It implies that coaches and trainers should be encouraged to couple aerobic exercise intensities with complex task switching tasks. Learning experiences in strategic sports should be structured in a manner that does not involve repetitive action plans, which reinforce perseverative tendencies in the sequence of action choices, but instead involve frequent changes of stimulus–response mapping to promote cognitive flexibility. The activation of processing resources induced by aerobic exercise may maximize the effects of training situations requiring frequent task-set reconfigurations.

For future research, it will be important to extend the investigation of the impact of cognitive expertise and aging on cognitive flexibility, both at rest and during physical exercise. It is important to consider that in strategic team sports, there is an advantage not only to be skilled in coping with unpredictable events generated by opponents, but also to behave as unpredictably as possible (Glimcher, 2003). Being unpredictable is in essence an executive problem requiring one to overcome nonrandomness in thought and action and insulating decision against contextual interference (Mayr & Bell, 2006). To tap this aspect of cognitive flexibility, in future research, it may be useful to enhance task representativeness using voluntary task-switching paradigms in which individuals must select randomly between competing tasks, counteracting a natural bias toward perseveration. Finally, multiple switch cost measures should be used, as aging and cognitive efficiency seem to influence different processes underlying switch cost performances (Adrover-Roig & Barcelò, 2010).

**Notes**

1. Although mean RTs are more commonly used in exercise and cognition research, we used median RTs to reduce potential artifacts deriving from higher rates of outliers in old individuals that disproportionally contribute on mean RTs. In addition, a preliminary calculation of both median and mean RTs showed the following trend: median RT < mean RT without inclusion of outliers deviating more than 2 $SD <$ mean RT including outliers, with largest differences in the old group. Considering that RT distributions are usually positively skewed, this computation confirmed that the median is the smallest overestimate, and is thus the appropriate measure, particularly when RT differences, not absolute RTs, are relevant (Robertson, Egly, Lamb, & Kerth, 1993).

2. To overcome potential artifacts deriving from the longer RTs and larger interindividually variability of older individuals, proportional switch cost scores were submitted to analysis. They were calculated according to the formulas $(\text{RT}_{\text{STG}} - \text{RT}_{\text{NSG}}) / \left[ (\text{RT}_{\text{STG}} + \text{RT}_{\text{NSG}})/2 \right]$ for local-to-global switch costs and $(\text{RT}_{\text{STL}} - \text{RT}_{\text{NSL}}) / \left[ (\text{RT}_{\text{STL}} + \text{RT}_{\text{NSL}})/2 \right]$ for global-to-local switch costs. All results of the analyses performed on absolute switch costs were confirmed by the analyses performed on proportional switch cost scores. Thus, any effect of age on switch costs could not be due to the fact that the higher RT of older adults enhances the magnitude of RT differences between conditions.
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References


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