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Exercise-induced arousal affects free-choices to inhibit

Tommaso Dall'Acqua[a,*], Chunting Li[a], Francesco Ceccarini[a], Davide Grigoletto[b], Giuseppe Marcolin[b], Antonio Paoli[b], Umberto Castiello[a,c,d]

[a] Dipartimento di Psicologia Generale, Università di Padova, Padova, Italy
[b] Dipartimento di Scienze Biomediche, Università di Padova, Italy
[c] Center for Cognitive Neuroscience, Università di Padova, Padova, Italy
[d] Centro Linceo Interdisciplinare Beniamino Segre, Accademia dei Lincei, Roma, Italy

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ABSTRACT

Objectives: Previous research has demonstrated that exercise–induced arousal has the ability to improve the stopping of an already initiated response. So far the effects of arousal on response inhibition have been investigated with paradigms concerned with inhibition driven by external stimuli. Since in everyday life situations the origin of decisions to inhibit might be entirely internally driven, the present study aims to explore whether intentional action and inhibition responses depend on the physical exertion in a cycle ergometer test.

Design and method: While cycling in conditions of low and high exercise-induced arousal, participants were asked to respond to cued and free-choice targets following the presentation of three varieties of masked primes that could elicit congruent or incongruent prime-response conflicts.

Results: In condition of high exercise-induced arousal an improvement on reaction times was observed in both cued and free-choice action conditions and less omission errors in cued action trials. Concerning free-choice behavior, overall participants made more 'action' choices when compared to the low arousal condition.

Conclusions: Our results widen previous evidence by showing that as for externally driven cognitive processes, also intentional action and inhibition choices are modulated by exercise. Under specific conditions arousal helps individuals to perform the tasks rapidly and efficiently even when task' requirements are entirely internally driven. However higher-order processes, such as making a free-choice, resulted impaired.

1. Introduction

Response inhibition is generally considered a prominent sub-component of cognitive control which is part of executive functions (Bari & Robbins, 2013; Veen & Carter, 2006). Such higher-order supervisory and executive system has the ability to withhold lower-order behavioral impulses preventing responses that might lead to inappropriate or even dangerous outcomes. 'Go/No-go' and 'Stop Signal' tasks (SST) are frequently adopted to investigate inhibition (van den Wildenberg et al., 2010). These tasks require participants to stop an ongoing behavior in response to an external stimulus.

One of the questions attracting the interest of those working in this research field is whether modulating the level of arousal could influence higher-level cognitive functions such as response inhibition. For instance, Weinbach, Kalanthroff, Avnit, and Henik (2015) included an alerting cue (i.e., an irrelevant stimulus) in a SST to increase participants' level of arousal for a short period of time. Interestingly, the increase of the arousal induced by the alerting cue reduced reactions times (RT) to go stimuli on one hand and shortened the stop-signal reaction times (SSRT; which is a measure of efficacy of the inhibitory processes) on the other, indicating an improvement in response inhibition. In the authors' perspective, the results highlight the role of basic, lower-level mechanisms in modulating complex, higher-level cognitive processes such as inhibitory control to produce well-coordinated action (Weinbach et al., 2015).

Along the same lines it has been advanced that exercise–induced arousal has selective effects on cognitive processing. Exercise appears to facilitate certain aspects of processing such as response speed and accuracy and to enhance the processes involved in problem-solving and goal-oriented actions (Chang, Labban, Gapin, & Etnier, 2012; Tomporowski, 2003). Accordingly, a study by Chu, Alderman, Wei, and Chang (2015) tested the effects of acute exercise on the inhibitory aspect of executive function using behavioral and electrophysiological approaches. To examine the effects of exercise-induced arousal on motor response inhibition, college students underwent a SST following acute aerobic exercise. The level of exercise was determined via the

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[*] Corresponding author. Dipartimento di Psicologia Generale, Università di Padova, via Venezia 8, 35131, Padova, Italy.
E-mail address: tommaso.dallacqua@phd.unipd.it (T. Dall'Acqua).

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submaximal treadmill walking test (SSTWT) carried out prior to behavioral testing. A sedentary control session, that involved reading, was also included. The main findings from this study suggest that acute exercise results in a shorter SSRT, but does not alter the go RT (Chu et al., 2015).

Overall, the aforementioned studies suggest that exercise-induced arousal has the ability to improve cognitive functions such as response inhibition. Much of the existing work examining the association of exercise and cognitive functions derives from 'arousal theories' (e.g., Hockey, 1997; Kahneman, 1973; Sanders, 1983; Yerkes & Dodson, 1908). The common denominator of these theories is the function assigned to arousal in facilitating the allocation of metabolic resources and attentional focus in order to meet the specific task demands (Audiffren, Tomporowski, & Zagrodnik, 2008). In particular, exercise would stimulate the arousal system in the brainstem, disinhibiting the production of neurotransmitters such as norepinephrine and dopamine thus improving the quality of task's execution by enhancing speed and accuracy (Robbins & Everitt, 1995). The gradual metabolic recovery and the higher level of arousal occurring after exercise facilitate cognitive processing (Audiffren et al., 2008; Tomporowski, 2003). Although a general positive effect on cognitive performances tested after exercise is well established, for cognitive performances tested during exercise a different explanation has been recently proposed. The transient hypofrontality theory (THT) posits that during exercise, higher-order computations of prefrontal cortices and the actual motor implementation compete for the allocation of limited metabolic resources (Dietrich, 2003, 2006). Since cognitive processing is set to a lower priority during exercise, available resources are drawn from the brain regions that are not essential to perform the exercise, provoking a decline in complex mental processing. However, cognitive performances that rely on more automatic brain processes (e.g., reaction times, response accuracy, stimulus detection) would be enhanced due to a downregulation of the frontal cortex and consequent disinhibition of the arousal networks in the brainstem. Depending on the different moderators that are taken into account (e.g., type of cognitive performance, fitness level, task duration), mixed finding are reported for cognitive abilities tested during exercise. In this respect, some results support the THT (Lambourne & Tomporowski, 2010) whereas others (Chang et al., 2012) do not.

So far, the effects of arousal on response inhibition have been investigated with paradigms concerned with inhibition driven by external stimuli (Logan & Cowan, 1984; Verbruggen & Logan, 2008). However, a recent line of research has proposed that along with inhibition driven by an external stimulus, a more intentional mechanism might be recruited to withhold from executing a pre-potent action tendency (Brass & Haggard, 2007; Filevich, Kühn, & Haggard, 2012). The so-called 'intentional inhibition' has been tested by means of specifically tailored experiments in which participants were free to decide whether to execute or inhibit a particular behavior (Kuhn, Gevers, & Brass, 2009). In this view, the term 'intentional inhibition' captures the process of deciding between intentionally performing and intentionally inhibiting a prepared action, up until the very last moment (Brass & Haggard, 2007, 2008; Filevich et al., 2012). Intentional inhibition has been conceptualized as a late veto before action execution, a final check that recruits cortical mechanisms partially distinguishable from those characterizing stimulus-driven inhibition (Kühn, Haggard, & Brass, 2009).

An attempt to behaviorally operationalize intentional inhibition comes from a study of Parkinson and Haggard (2014). This work was based on the notion that subliminal perceptual priming can manipulate the subjective experience of the agency of a "free" action (Aarts, Custers, & Wegner, 2005; Sato, 2009; Sebanz & Lackner, 2007; Wenke, Fleming, & Haggard, 2010) and influence a "free" decision regarding which action to select (Schlaghecken & Eimer, 2004; Teuchies et al., 2016). In this modified version of the Go/No-go task, participants made speeded key-press actions to a go target or withheld responses to a no-go target or made free, spontaneous choices whether to execute or inhibit a keypress when presented with a free-choice target. Prior to each target, subliminal masked prime arrows were presented. Primes could be congruent with the go or no-go arrows, or neutral. RTs and proportion of action choices were measured. Primes were presented at latencies that would give either positive or negative compatibility effects based on previous literature. Crucially, results showed that when go primes were presented at negative-compatibility latencies, "free" decisions to inhibit significantly increased (Parkinson & Haggard, 2014). Thus, it appeared that decisions to act or not can be unconsciously manipulated, at least by inhibitory mechanisms. The cognitive mechanisms responsible for intentional inhibition can be influenced by unconscious processing.

The present study capitalized on this paradigm to investigate whether arousal had the ability to modulate intentional inhibition as previously reported for external kind of inhibition (Chu et al., 2015; Weinbach et al., 2015). In particular, participants were required to respond to three possible target stimuli (arrows) in three different conditions: (i) cued action condition, in which the choice to act is indicated by a cue (cued go targets); (ii) cued inhibition condition, in which the choice not to act is indicated by a cue (cued no-go targets); or (iii) free-choice condition, in which participants were free to choose whether to act or not (free-choice targets). The targets were preceded by masked primes (arrows), whose direction could be congruent or incongruent with the go and no-go target (i.e., pointing to the same or the opposite direction) or neutral (i.e., pointing toward no specific direction). By asking participants to perform the task while pedaling on a cycle ergometer, the paradigm was administered at a different level of workload intensities with the specific purpose of eliciting different levels of exercise–induced arousal.

In line with previous evidence (Parkinson & Haggard, 2014), RTs to cued go targets are expected to be speeded up by congruent prime/target combinations and slowed down by incongruent prime/target combinations. The same pattern should characterize action trials in free-choice conditions. Consistently, in cued conditions a higher proportion of errors is hypothesized (omissions and false alarms) for incongruent prime/target combinations compared to congruent prime/target combinations. Moreover, go primes are expected to increase the proportion of free-choices to act, and no-go primes to increase the proportion of free-choices to inhibit the action, if compared to neutral primes. The effects of arousal are predicted to be twofold. On the one side arousal would modulate low-level processing enhancing RTs and accuracy. On the other side, according to the THT (Dietrich, 2003, 2006), free-choice performance should be disrupted by the arousal manipulation due to an impairment of high-level executive functions responsible for the decisional and attentional processing. Likewise, this is expected to boost the effect of subliminal primes. RTs of cued and free-choice trials would be shortened in the high arousal condition when compared to the low arousal condition. Further, the pattern induced by subliminal priming is expected to be consistent between low and high arousal conditions, namely faster RTs after a go prime and slower RTs after a no-go prime. In line with previous evidence, higher arousal is predicted to improve response accuracy reducing the number of errors in cued conditions (omissions and false alarms). With respect to the proportion of choices to act or to inhibit in free-choice trials a general increase of choices to act in high arousal condition is expected, due to enhanced impulsiveness and disinhibition in the decisional processes involved by the task. Although improved accuracy in cued trials is expected in the high arousal condition, when no specific control is required (i.e., in free-choice trials where there are no right or wrong responses) priming might affect responses differently. For this reason the impulsiveness and disinhibition of attentional resources elicited by the high arousal condition is expected to produce a stronger effect of the subliminal priming on the proportion of free-choices: go primes would increase the proportion of actions and no-go primes would increase the proportion of inhibition choices more for the high compared to the low arousal condition.

2. Method

2.1. Participants

In order to determine the appropriate sample size for this study, a priori power analysis was conducted using a freely-available software (G*Power 3.1.9; Faul, Erdfelder, Lang, & Buchner, 2007). The effect-size calculation was based on a recent review on the effect of acute exercise on cognitive performances (Chang et al., 2012). The optimum sample size of 15 participants was calculated by fixing the probability of a type 1 error at an alpha of 0.05, to yield 0.80 power for an effect size of 0.23. Because of the possibility that a small number of participants would produce unreliable free-choice data within this kind of paradigms (Parkinson & Haggard, 2014) a total of 20 healthy volunteers participated in the study after giving oral and written consent. Data of one participant were discarded because of an excessive tendency to prefer inhibition in free-choice trials (2.34%, < 2.5 *SD* from sample mean), which rendered free-choice data potentially unreliable. All analyses were conducted on the remaining nineteen participants (13 female, mean age = 25.36 years, *SD*: ± 0.67). All participants had normal or correct-to-normal vision and were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). Despite the low-risk physical effort required by the test the following exclusion criteria were adopted to ensure the homogeneity of the sample: hypertension, diabetes, heart diseases and obesity (Body Mass Index, BMI $>$ 30) or severe underweight (BMI $<$ 16). This information was collected with a self-report questionnaire. The study was conducted according to the guidelines provided by the Declaration of Helsinki and the ethical requirements of the University of Padua. Demographic and fitness data are presented in Supplementary Table 1.

2.2. Sub-maximal workload test

Since equivalent workload intensities might correspond to a different level of fatigue depending on participants' individual fitness level, personalized workload intensities were calculated corresponding to the 30% of the predicted maximal load (Load_{max}) for each participant. In order to determine this percentage of Load_{max}, participants underwent the YMCA sub-maximal cycle ergometer test (Beekley et al., 2004; Pescatello & American College of Sports Medicine, 2014). This test allowed to determine the predicted Load_{max} at the age-predicted maximum heart rate (HR_{max}; e.g., 220 minus age). The protocol for this test consisted of four three-minute stages (12 min in total) with increasing workload intensities starting at 25 W for the first stage. At the second stage, the workload intensity was raised to a specific value based on the stabilized heart rate frequency collected at the end of the first stage. If the heart rate frequency was lower than 90 bpm the second stage was set to 100 W, if higher than 90 bpm, but lower than 100 bpm it was set to 75 W and if higher than 100 bpm to 50 W. The third and the fourth stages consisted of increments of 25 W each. Throughout the whole test participants were required to maintain a cadence of 60 rpm (rate per minute). Heart rate data were collected through a chest band (Polar, Kempele, Finland) and subjective experience of exertion throughout the test was recorded by means of a 6–20 Borg scale (Haile, Gallagher, & J. Robertson, 2015) at the end of each stage. Before the test, participants were asked to warm-up for two minutes pedaling at 25 W gradually reaching the cadence of 60 rpm. At the end of the test a cool-down period was ensured consisting of a continuation of the exercise with watt load equivalent to the first stage of the test protocol gradually decreasing cadence. Heart rate was monitored for a surveillance period until stabilized.

2.3. Design

The study was divided into an *assessment* session and two experimental sessions: *baseline* and *physical-load*. In the *assessment* session the experimenter gave only a brief introduction of the study and participants filled the informed consent and exclusion criteria form. All participants that met the criteria underwent the 'sub-maximal workload test' during the same session. The *assessment* session was at least 24 h distant from the other two sessions. During both the *baseline* and the *physical-load* sessions, participants completed the computer-based task while cycling under two different workload conditions in order to elicit two different levels of arousal. In the *baseline* session the experimenter put the heart rate monitor on participants' chest and asked them to start cycling at 60 rpm with 25 W load. While warming-up participants read the instruction on the monitor in front of them. About 2 min of warm-up was ensured for each participant. After this time participants were allowed to start whenever they felt ready by simply pressing the response button. During the whole session participants needed to maintain the speed constant while the watt remained unchanged and the heart rate frequency was monitored throughout. At task completion they were asked to continue pedaling for a cool-down phase at a lower work rate up until their heart rate significantly decreased and they felt ready to stop the exercise. The experimental setting and procedure for the *physical-load* session were the same as the *baseline* session, the only difference regarded the heightened watt load intensity which caused an increase of the exercise-induced arousal. Based on the performance on the 'sub-maximal workload test' a customized watt load was assigned to each participant for the *physical-load* session. Since they were asked to maintain the cadence of 60 rpm constant, the physical effort required in this session was considerably higher compared to the *baseline* session. During both experimental sessions the heart rate frequency was collected at the beginning of the task and at the end of each block. The sequence of the *baseline* and *physical-load* sessions was randomly assigned across participants on the second and third visit to eliminate possible biases based on order and learning effects. For all participants the two sessions occurred approximately one week apart.

2.4. Stimuli

The paradigm included three different prime stimuli and three target stimuli. Prime stimuli were white arrows either pointing up, down or neutral (overlapping up and down primes). The target stimuli followed the primes and were formed by the contour of either upward, downward or double headed pointing arrows. Targets surrounded a meta-contrast mask that superimposing the primes obstructed their visibility. Primes subtended a visual angle of $0.6^\circ \times 1.8^\circ$, targets of $1.4^\circ \times 3.8^\circ$ and the mask of $1^\circ \times 2.2^\circ$. Both the prime and the target stimuli were presented on a black background and were aligned to a fixation cross in the middle of the screen. Stimuli shapes and dimensions are shown in Supplementary Fig. 1.

2.5. Procedure

A representation of the experimental setup and an example of a trial sequence are shown in Fig. 1. Participants were seated in a dimly lit room on a cycle ergometer (Ergoselect 200, Ergoline GmbH, Germany) at a distance of 60 cm from a PC-driven CRT monitor (resolution 1280 × 1024; 75 Hz refresh rate) positioned on a tripod, with the center of the screen set at the eye level. Responses were given with the index finger of the right (dominant) hand using a response button fixed on the handlebar of the cycle ergometer. All trials started with a fixation cross (subtending 0.3°) that appeared in the center of the screen for 534 ms and was followed by a masked prime stimulus (from now on defined as 'prime') presented for 13 ms (1 frame at 75Hz $\approx$ 13.3 ms). Following the presentation of the prime, a fixation cross of 39 ms duration and subsequently the target surrounding a meta-contrast mask

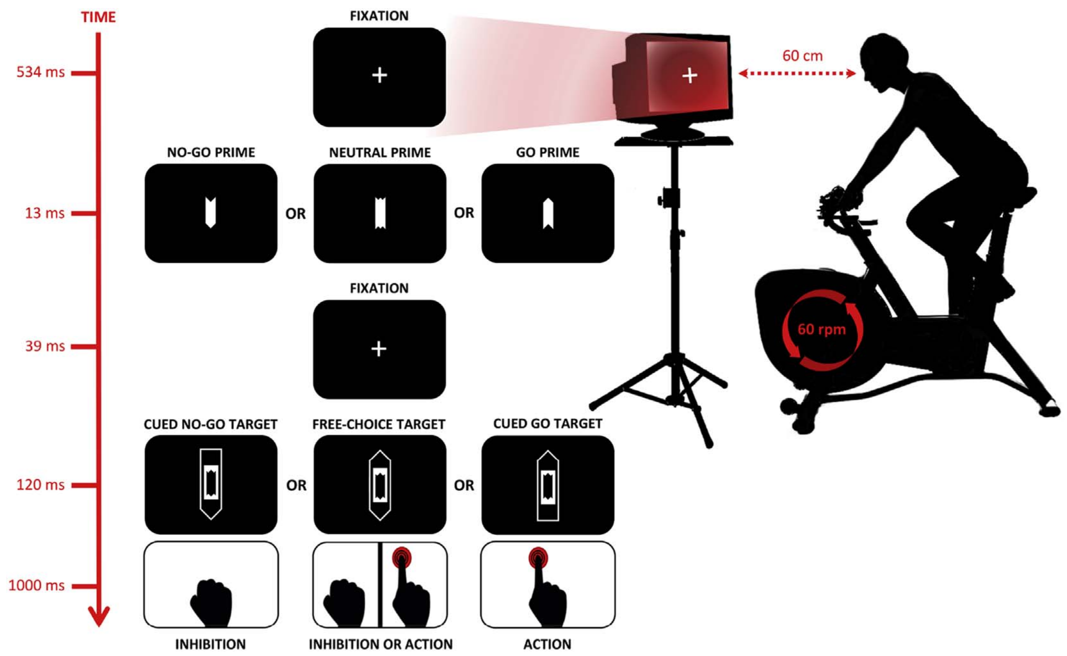

Fig. 1. A schematic representation of the experimental setup and the stimulus schema including the timing and the masked prime/target combinations. In the proposed example the upward arrows indicate the cued go signal; rpm: revolution per minute.

appeared. Both the target and the mask lasted for 120 ms. Having the same luminance as the prime, this backward stimulus sequence has been shown to effectively obstruct the visibility of the prime stimulus (Lingnau & Vorberg, 2005). Accordingly to the direction of the target stimuli, the trials of each block consisted in: cued go, cued no-go and free-choice trials. Prior to the beginning of each experimental block, participants received instructions about the identity of the go target (upward or downward pointing arrow) and they were requested to respond as quickly and accurately as possible by pressing the response button. In the same block, the no-go target consisted of an arrow pointing in the opposite direction of the go target. At the sight of the no-go target, participants were required to refrain from responding. Furthermore, they were told that a double-headed target arrow always represented a free-choice target on the basis of which they freely decided whether to answer or to inhibit their response. They were asked to avoid using strategies (e.g., alternating between action and inhibition), differentiating their decisions throughout the whole experiment. Since speed was stressed to lead participants preparing the action at the beginning of every trial, they had to decide at the very last moment whether to carry out their response or not. The response window was set at 1000 ms, starting from the appearance of the target. The prime stimuli were categorized in accordance with the direction of the target stimuli. In particular, go primes pointed in the same direction of the go targets; no-go primes in the same direction of no-go targets and neutral primes (overlapping up and down primes) served as control conditions. Task presentation and response registration were controlled using E-prime 2.0 experimental software (http://www.pstnet.com/eprime.cfm). Each experimental session was split in 4 blocks lasting approximately 6 min each, for a total of ~25 min. A total of 384 trials (96 trials per block) was administered, divided into: 25% go targets, 25% no-go targets and 50% free-choice targets. Each target was preceded by go, no-go or neutral primes, with equal probability (33.3%). An equal number of go and no-go stimuli has been adopted to avoid the 'oddball' effect of no-go stimuli (A. A. Stevens, Skudlarski, Gatenby, & Gore, 2000). Moreover a disproportion of cued go and no-go stimuli would inevitably create a tendency toward acting or inhibiting that could bias participants' responses in free-choice trials. The inter-stimulus interval (ISI) was randomized and lasted between 2000 and 2500 ms. During both experimental sessions participants remained unaware of the presence of the prime. After the last experimental session, participants were informed about the presence of the masked primes, and were asked to take part in a short testing phase to verify primes discriminability. A total of 30 testing trials was administered (10 repetitions for each of the three prime stimuli): testing trials were identical to free-choice trials, but participants were asked to focus on prime appearance and ignore the target, trying to decide whether the prime was pointing up, down, or was neutral, by making unspeeded but forced choices. In case of uncertainty, they were instructed to simply guess. During this last brief phase they were asked to continue cycling, with the purpose of reproducing the same experimental conditions of the experimental sessions. Participants were trained to familiarize with the task instructions during a training session in a separate room prior to the beginning of each experimental session.

2.6. Statistical analyses

Statistical analyses on the effects of interest were computed by means of linear mixed-effects (LME) models (for RTs and heart rate variability) and generalized mixed-effects (GLME) models with a binomial link function (for free-choice behavior and error rates; Pinheiro & Bates, 2000). As compared to traditional repeated-measures ANOVA approach, LME and GLME provide greater statistical power for the analysis of repeated observations and provide a robust method of dealing with unbalanced data such as in the present experiments (Baayen, Davidson, & Bates, 2008). LME and GLME models allow to consider simultaneously the standard fixed-effects factors controlled by the experimenter and the random-effects factors. For the LME and GLME models used in this study, random effects consisted of participants and experimental block. Models were fitted using Restricted Maximum Likelihood (REML). For the computation of the models, R (R Core Team, 2017), lme4 (Bates, Mächler, Bolker, & Walker, 2015), nlme (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2017), and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2014) were used. P-values were estimated by likelihood ratio tests of the full model with the effect in question against the model without the effect in question. The strength of the evidence in favor of one model over the other is reported as the relative likelihood based on the models' Akaike Information Criterion (AIC) computed as $AIC_{RL} = \exp((AIC_{M1} - AIC_{M2})/2)$, where '$AIC_{RL}$'

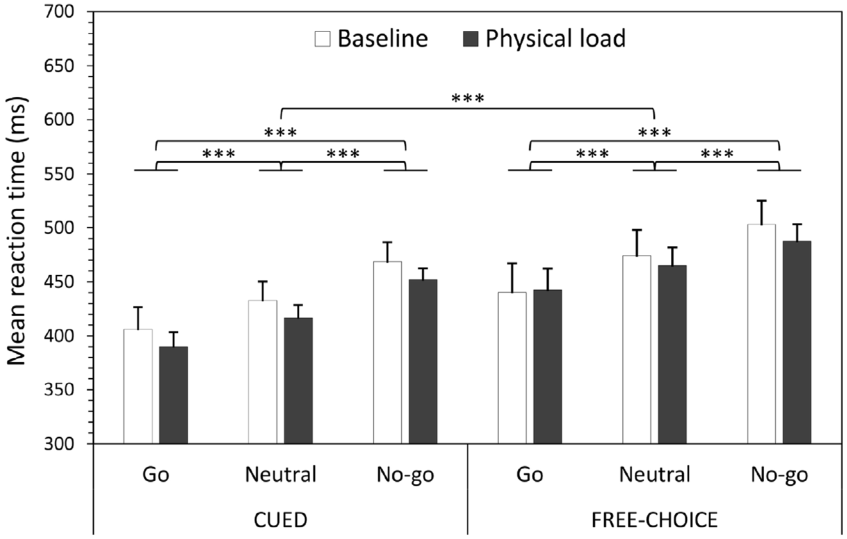

Fig. 2. Mean RTs in milliseconds (ms) for go trials (cued and free-choice trials) split for each type of prime (go, no-go and neutral) in both experimental sessions (baseline and physical load). Error bars show standard error of mean. ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

represents the relative likelihood of the model with the effect in question, and 'AIC_{M1}' 'AIC_{M2}' the comparison between the two models (Akaike, 1987; Burnham & Anderson, 2010; Wagenmakers & Farrell, 2004). As preliminary analysis, individual heart-rate variability within each experimental session was controlled to ensure that participants' heart rate frequency was kept constant throughout the blocks, indicating that a stable level of exercise-induced arousal was maintained during the whole session. Each level of the independent variable consisted of five time-points, one at the beginning of the experiment and four at the end of each block. A LME model on heart rate frequency with Time (T1, T2, T3, T4, T5) and Session (Baseline, Physical load) as fixed effects was computed. As second preliminary analysis, to guarantee that unconscious perception of the prime was preserved for all participants, the results from the prime discrimination test were calculated as the mean percentage of primes correctly discriminated compared against the chance level of 33.3% accuracy. For the main analyses, RTs were obtained from participants' correct responses to go targets (cued go trials) and to free-choice targets when participants chose to press the button to answer (free-choice go trials). For RTs an LME model was computed with Prime (Go, No-go, Neutral), Target (Cued go, Free-choice go) and Session (Baseline, Physical load) as fixed effects. RTs outliers were removed following a two-steps procedure (Baayen & Milin, 2015): first, extremely shorts (< 200 ms) and extremely long (> 1000 ms) RTs were removed (less than 0.5% of the data). Second, after the standardized residuals of the full LME model have been computed, trials with absolute standardized residuals exceeding ± 2.5 *SD* were discarded (about 2.5% of the data). Free-choice trials were analysed in order to uncover how masked priming influenced participants' choice to execute or inhibit the actions in both low and high arousal conditions. The number of choices to act or to inhibit as a function of subliminal primes was computed by fitting a GLME model with Prime (Go, No-go, Neutral) and Session (Baseline, Physical load) as fixed effects. Since participants were asked to avoid the use of strategies (e.g., alternating between action and inhibition), free-choice trials have been further explored by looking at sequential dependencies between trials in both low and high arousal conditions. Responses in the current free-choice trial (trial *n*) with those in the previous trial (trial *n-1*, which could either be a cued trial or another free-choice trial) were compared to see whether participants had a tendency to systematically respond the same (action – action; inhibition – inhibition) or the opposite (action – inhibition; inhibition – action) in trial *n* as in trial *n-1*. A GLME model was computed with Previous choice (Action, Inhibition) and Session (Baseline, Physical load) as fixed effects and the choice at trial *n* as dependent variable. In conclusion, error rates within each cued condition (omissions in cued action trials and false alarms in cued inhibition trials) were computed for each session as function of the subliminal prime by fitting GLME model with Prime (Go, No-go, Neutral) and Session (Baseline, Physical load) as fixed effects. For both GLME and LME models, post-hoc analyses were performed on effects of interests by means of planned pair-wise comparisons (*t*-tests) and the α level was set at 0.05 prior to Bonferroni correction. Cohen's *d* indices are reported as measure of effect sizes (Cohen, 1988).

3. Results

3.1. Preliminary analyses and prime discrimination

As preliminary control measure, heart rate frequency collected during the sub-maximal workload test correlated positively with participants' responses to the Borg scale, $r(74) = 0.734$, $p < 0.001$. Regarding the experimental sessions, the preliminary analysis on heart rate variability revealed a statistical significant effect of Session, $\chi^2(1) = 149.63$, $p < 0.001$, $\text{AIC}_{\text{RL}} = 5.85$, but not of Time, $\chi^2(4) = 1.99$, $p = 0.737$, $\text{AIC}_{\text{RL}} = 0.05$, and neither the interaction Session by Time, $\chi^2(4) = 0.445$, $p = 0.978$, $\text{AIC}_{\text{RL}} = 0.02$. On average heart rate frequency was modulated by the low and the high arousal condition (baseline: $M = 100.42$, ± 12.1 *SD*; physical load: $M = 114.53$, ± 8.69 *SD*), but within each condition the frequency was maintained constant (see Supplementary Fig. 2). The results of the prime discrimination test showed that primes were not consciously detected, $t(18) = 0.668$, $p = 0.689$, tested against the 33.3% chance level (mean correct: $M = 30.6\%$, ± 5.23 *SD*). As a measure of discriminability, *d'* was computed for each prime/participant. The obtained *d'* values were not significantly different from '0' (no discrimination possible), $t(18) = 0.575$, $\text{p} = 0.722$ (*d'* values: $M = 0.31$, ± 0.06 *SD*).

3.2. Reaction times

Fig. 2 summarizes the mean RTs for each type of prime and for both experimental sessions. The analysis on RTs yielded a significant main effect of Prime, $\chi^2(2) = 392.79$, $p < 0.001$, $AIC_{RL} > 100$, Target, $\chi^2(1) = 398.03$, $p < 0.001$, $AIC_{RL} > 100$, and Session, $\chi^2(1) = 53.89$, $p < 0.001$, $AIC_{RL} > 100$. Although the main effect of Session indicates that in the high arousal condition (Physical load) the RTs were faster, $t(18) = 3.60$, $p < 0.001$, $d = 0.086$, the lack of the significant interactions Prime by Session, $\chi^2(2) = 3.06$, $p = 0.216$, $AIC_{RL} = 0.62$, and Target by Session, $\chi^2(1) = 1.66$, $p = 0.196$, $AIC_{RL} = 0.84$, indicates that primes and targets were elaborated similarly in the two conditions. The main effect of prime indicates that response timing was faster if preceded by go primes when compared to neutral, $t(18) = 7.72$, $p < 0.001$, $d = 0.213$, or no-go, $t(18) = 16.86$, $p < 0.001$, $d = 0.482$, primes. Conversely, no-go primes slowed down the response if compared to neutral primes, $t(18) = 9.02$, $p < 0.001$, $d = 0.281$. Following, the significant main effect of target indicates that responses to cued go targets were faster compared to the free-choice go targets overall, $t(18) = 14.38$, $p < 0.001$. The interaction Prime x Target was significant, $\chi^2(2) = 8.54$, $p = 0.013$, $\mathrm{AIC}_{RL} = 9.69$, indicating that the effect induced by go primes was smaller in the cued condition but the effect induced by no-go primes was smaller in the free-choice condition: Cued neutral prime – Cued go prime (mean difference: $M = 26$ ms), $t(18) = 6.56$, $p < 0.001$, $d = 0.266$; Free-choice neutral prime – Free-choice go prime ($M = 28$ ms), $t(18) = 5.63$, $p < 0.001$, $d = 0.218$; Cued no-go prime – Cued neutral prime ($M = 36$ ms), $t(18) = 8.74$, $p < 0.001$, $d = 0.391$; Free-choice no-go prime – Free-choice neutral prime ($M = 26$ ms), $t(18) = 4.95$, $p < 0.001$, $d = 0.216$.

3.3. Free-choice behavior

For the free-choice condition the analysis looked at how the primes biased the choices made by participants. The response bias was defined as the percentage of free-choice trials in which each participant chose to respond as a function of the preceding masked prime. The analysis showed a main effect of Prime, $\chi^2(2) = 98.72$, $p < 0.001$, $\mathrm{AIC}_{RL} > 100$ and a main effect of Session, $\chi^2(1) = 17.67$, $p < 0.001$, $\mathrm{AIC}_{RL} > 100$, but not a significant interaction Prime by Session, $\chi^2(2) = 3.29$, $p = 0.193$, $\mathrm{AIC}_{RL} = 0.69$, indicating that once again the effect of priming, although present, was similar for both low and high arousal conditions (see Fig. 3). Participants chose to respond after a go prime more often when compared to neutral primes: go – neutral (mean difference: $M = 9\%$), $t(18) = 6.43$, $p < 0.001$, $d = 0.179$; or when compared to no-go primes: go – no-go ($M = 13\%$), $t(18) = 9.22$, $p < 0.001$, $d = 0.261$; and chose more often to inhibit the response after a no-go prime if compared to a neutral prime: neutral – no-go ($M = 4\%$), $t(18) = 2.79$, $p = 0.015$, $d = 0.081$. Interestingly, overall participants were less prone to inhibit the response in the physical load condition when compared to the baseline condition: physical load – baseline ($M = 5\%$), $t(18) = 4.10$, $p < 0.001$, $d = 0.098$. Looking at the sequential dependencies in free-choice trials, neither the Previous choice regressor, $\chi^2(1) = 3.20$, $p = 0.073$, $\mathrm{AIC}_{RL} = 0.54$, nor the Previous choice by Session interaction, $\chi^2(1) = 0.23$, $p = 0.626$, $\mathrm{AIC}_{RL} = 0.41$, were significant. Participants chose to respond action (*n*) after an action trial (*n-1*) 52% of the times, and chose to respond inhibition (*n*) after an inhibition trial (*n-1*) 50% of the times. The lack of significance indicates that the response to trial *n-1* was not biasing the response to trial *n* neither by inducing an increase of switches nor by systematically repeating the same response. This result supports the conclusion that participants have been responding in a balanced and random way at the best of their possibilities as requested by the experimenter. The main effect of Session was significant $\chi^2(1) = 18.02$, $p < 0.001$, $\mathrm{AIC}_{RL} > 100$, replicating the result of the previous analysis showing that participants chose to respond more in the physical load condition overall.

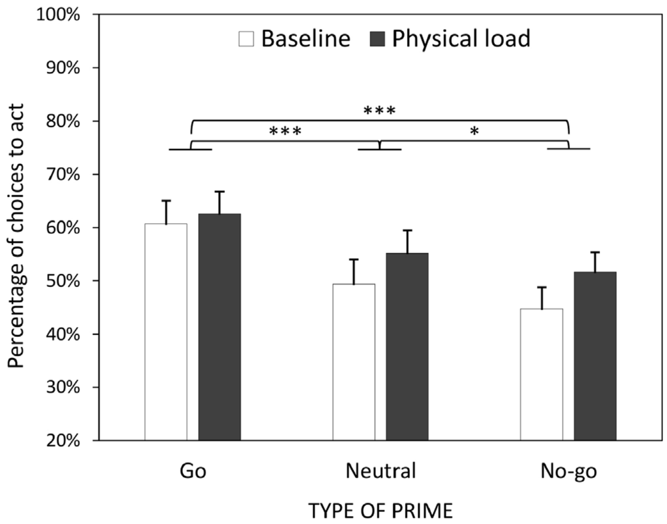

Fig. 3. Mean percentage of free-choice trials in which participants chose to act rather than inhibit responses, as modulated by type of primes (go, no-go and neutral) and experimental sessions (baseline and physical load). Error bars show standard error of mean. $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

3.4. Error rates

Looking at both experimental sessions, errors in cued trials were generally a few. Within cued inhibition trials the mean rate of false alarms was 8.6%. The GLME model on false alarms yielded a significant main effect of Prime, $\chi^2(2) = 47.80$, $p < 0.001$, $\mathrm{AIC}_{RL} > 100$, but not of Session, $\chi^2(1) = 1.16$, $p = 0.279$, $\mathrm{AIC}_{RL} = 0.66$, or the interaction Prime by Session, $\chi^2(2) = 0.77$, $p = 0.678$, $\mathrm{AIC}_{RL} = 0.19$. The main effect of prime indicates that false alarms were more numerous after a go prime was presented (12.9%) if compared to neutral (7.3%) or no-go primes (5.7%), intuitively reflecting the incompatibility between the response suggested by the prime (go) and the response required by the target (no-go). Within cued action trials participants were more accurate and the mean rate of omissions was 4%. The GLME model on omissions yielded a significant main effect of Session, $\chi^2(1) = 4.27$, $p = 0.038$, $\mathrm{AIC}_{RL} = 3.11$, but not of Prime, $\chi^2(2) = 2.50$, $p = 0.286$, $\mathrm{AIC}_{RL} = 0.47$, or the interaction, $\chi^2(2) = 0.89$, $p = 0.638$, $\mathrm{AIC}_{RL} = 0.21$. In cued action trials the incompatibility between primes and target did not affect the general level of accuracy, however participants made significantly less errors in the physical load condition (3.4%) compared to the baseline condition (4.6%; see Supplementary Fig. 3). Mean values for each condition, percentage of errors in cued trials and percentage of responses in free-choice trials are reported in Table 1.

4. Discussion

The present study sought to investigate whether performing or inhibiting responses depended on the physical exertion in a cycle ergometer test. More in detail the study explored whether cued and free-choices among alternative outcomes (action or inhibition) are modulated differently by non-consciously perceived visual information in conditions of low and high exercise-induced arousal. While cycling, participants were asked to respond to cued and free-choice targets following the presentation of three varieties of masked primes that could elicit congruent or incongruent prime-response conflicts. Intentional actions and inhibition responses were compared, with stimulus driven responses. To introduce the arousal manipulation, personalized workload intensities were calculated according to participants' fitness level prior to the experiment. To our knowledge this is the first study attempting to explore the role of arousal as mediator in these processes. Since intentional inhibition might better describe everyday life situations (Brass & Haggard, 2007; Filevich et al., 2012), where no specific signals to stop are provided, defining its precise function is of utmost importance.

In line with the hypotheses, the behavioral results previously reported in Parkinson and Haggard (2014) have been replicated: for both baseline and physical load conditions, go primes had the ability to shorten RTs when compared to neutral primes. On the opposite, no-go primes determined longer RTs when compared to neutral primes. This effect was more pronounced in the cued compared to the free-choice condition as revealed by the interaction effect between primes and targets. As opposed to free-choice trials, in cued trials the response

Table 1

RTs and Standard Deviation (SD) in milliseconds of both free-choice and cued trials, percentage of errors in cued conditions, percentage of responses in free-choice condition, split for each prime (upper part), and collapsed across primes (lower part). Data are presented for each session separately (central columns) and collapsed across sessions (right column).

PRIME	TARGET	Baseline			Physical load			Baseline & Physical load		
		RTs (± *SD*)	% Errors	% Go responses	RTs (± *SD*)	% Errors	% Go responses	RTs (± *SD*)	% Errors	% Go responses
Go	Cued go	406 (± 109)	4.21		390 (± 94)	3.75		398 (± 102)	3.98	
Neutral	Cued go	432 (± 101)	4.06		416 (± 84)	2.81		424 (± 93)	3.43	
No-go	Cued go	468 (± 101)	5.62		452 (± 80)	3.59		460 (± 91)	4.60	
Go	Cued no-go		14.06			11.71			12.89	
Neutral	Cued no-go		7.65			7.03			7.34	
No-go	Cued no-go		5.62			5.78			5.70	
Go	Free-choice go	440 (± 141)		60.7	442 (± 132)		62.5	441 (± 136)		61.6
Neutral	Free-choice go	474 (± 126)		49.3	464 (± 115)		55.1	469 (± 120)		52.2
No-go	Free-choice go	502 (± 117)		44.7	487 (± 105)		51.6	494 (± 111)		48.2
Cued go		435 (± 107)	4.63		419 (± 89)	3.38		427 (± 99)	4.01	
Cued no-go			9.11			8.17			8.64	
Free-choice go		470 (± 132)		51.5	463 (± 120)		56.4	466 (± 125)		54.0
Cued & Free-choice go		453 (± 121)			443 (± 109)			448 (± 115)		

option (action or inhibition) was automatically triggered by the appearance of the cued go target. The retention of the information at the low-level of direct motor execution leaves less space for higher-level attentional control to compensate for the bias induced by the subliminal primes. This is further cleared up by the shorter RTs for the cued go conditions in comparison to those for the free-choice go conditions, intuitively reflecting the (high-level) decision processes involved in free-choices. As a secondary goal, the study tested whether it was possible to bias the free decision to withhold the response as demonstrated for free actions (Demanet, De Baene, Arrington, & Brass, 2013; Teuchies et al., 2016). Results showed that masked primes were able to induce the free decision process, both toward a significant increase of choices to act in action-congruent conditions, and toward an increase of choices to inhibit in inhibition-congruent conditions.

The primary interest of the present study was testing the impact of arousal on intentional action and inhibition, therefore the differences in participants' performances between the experimental sessions were investigated: RTs were shorter in the physical load session compared to the baseline session, for both cued and free-choice trials. Furthermore, the pattern evoked by each subliminal prime was consistent in the two arousal conditions. In line with previous literature indicating that exercise-induced arousal benefits performance on cognitive tasks (Tomporowski, 2003; Weinbach et al., 2015), not only participants responded faster but also were more accurate as demonstrated by the analysis on error rates (at least for the omissions).

It has been suggested that improvements in information processing during exercise are driven by alterations in brain neurotransmitter systems (McMorris, Tomporowski, & Audiffren, 2009). A neuroendocrinological model has been put forward to explain how diverse cognitive functions might be either facilitated or obstructed by specific exercise conditions (McMorris et al., 2009). According to this model, the onset of physical activity triggers a chain of hormonal responses that gradually escalate as exercise increases in intensity. Norepinephrine and dopamine, in particular, are thought to influence prefrontal lobe attentional systems by altering background neural noise relative to target saliency (Mesulam, 1990). An enhanced signal-to-noise ratio may improve stimulus encoding, decisional processes and response activation, and explain the reductions in our participants' response times during exercise (Lambourne & Tomporowski, 2010).

Concerning free-choice behavior, our results suggests that the number of choices to act or to inhibit was influenced differently by low or high arousal conditions. In particular, participants made more 'action' choices in the physical load condition overall. This result is in accordance with the THT (Dietrich, 2003, 2006) suggesting that, during exercise, the physical effort drawn important metabolic resources from the cortical areas responsible for executive functioning, disinhibiting low-level motor impulses originating in the brainstem. Moreover the behavioral effects may be further strengthened by the activation of the arousal system in the brainstem fostering impulsiveness in the decisional process linked to free-choice trials. This is in line with the evidence of reciprocal enhancing effects between arousal and impulsiveness in perceptual decision making (Murphy, Vandekerckhove, & Nieuwenhuis, 2014), time perception (Wittmann & Paulus, 2008), economic decisions (Jahedi, Deck, & Ariely, 2017), gambling (T. Stevens et al., 2015) and sexual behavior (Ariely & Loewenstein, 2006).

In contrast with our hypotheses, the lack of a significant interaction effect between prime and session, did not support the hypothesis of a strengthen effect of subliminal priming in the higher arousal condition. Although an increase in arousal did not correspond to an increase in the magnitude of the priming effect, subliminal primes preserved their modulatory pattern in both conditions. A possible reason for this lack of effect may be found in the level of exercise intensity that was selected for the physical load condition. According to the 'ACSM's guidelines for exercise testing and prescription' (Pescatello & American College of Sports Medicine, 2014) the 30% of Load$_{max}$ is considered a light exercise intensity. At this intensity, attentional resources may still preserve enough control on participants' free decisions as for the baseline condition, without being further disrupted by physical effort. Another possibility regards the moderate magnitude reported for subliminal priming' effects (Bermeitinger, 2016). A recent review on the effect of exercise on many cognitive domains indicated that acute exercise influenced participants' performance on some cognitive tests but not in others (Chang et al., 2012). Performance on tests that stressed information-processing speed and response speed was dependent on exercise demand, while tasks that required participants to make choice responses on the basis near-threshold perceptual discrimination were not (Chang et al., 2012). Similarly, the effects elicited by our subliminal manipulation may have not been robust enough to be dependent on exercise demands.

To sum up, in contrast with studies suggesting that an increase in arousal have the ability to improve the stopping of an already initiated response when driven by external stimulus (Chu et al., 2015; Weinbach et al., 2015), intentional inhibition did not benefit from the effect of arousal: the effect of subliminal primes was not reduced in the higher arousal condition as expected following an improvement of the executive control. On the contrary, arousal biased free-choices by increasing action choices overall, heightening impulsiveness and disinhibition of higher-order attentional control. In this circumstance, free decisions to inhibit seemed less voluntary determined if compared to the baseline condition. The effect of arousal on neurophysiological processes during exercise may account for the impact on basic bottom-up processes but has minimal or no effect on higher-level, top-down processes such as the control of the interference of subliminal irrelevant information. In light of this, we speculate that intentional inhibition and stimulus-driven inhibition might rely on partially distinct cognitive mechanism.

In this study subliminal priming of free decisions to inhibit has been evaluated within the laboratory setting. However, such types of effects are hardly generalizable to everyday motor control and remains unclear whether the mechanisms involved are determinant for real life situations. Nevertheless our results point out some intriguing considerations regarding team sports. Football athletes for example, continuously regulate their interactions with other players by both deciding on their own initiative 'the best athletic feat' for that specific game phase, and also through being able to inhibit the motor plan in reaction to an opponent's unexpected move. Concurrently, players are under great pressure caused by the physical exertion (the high level of arousal) and in that contingencies even a subtle change in the environment (like the prime) might be misinterpreted triggering an automatic but inappropriate move. An effective balance between action and inhibition is a very important factor to prevent the execution of inappropriate motor plans and any of its causal external effects. In these circumstances a deeper understanding of the cognitive mechanisms that govern the capacity to inhibit urges and actions would be of utmost importance.

5. Conclusions

The present study is the first to examine the effect of exercise–induced arousal on intentional action and inhibition. It extends previous literature by showing that not only externally driven processing benefits from an optimal exercise intensity. Under specific conditions exercise help individuals to perform the tasks rapidly and efficiently even when task's requirements are entirely internally driven. On the other hand, higher-order cognitive computations, such as making a free action choice, might be impaired. When compared to previous experimentation (for review see: Chang et al., 2012; Lambourne & Tomporowski, 2010), the experimental setup adopted in the present study considers some novel features that allow to draw firm conclusions on the issues at stake here. First, instead of employing a pre- and post-exercise measurement design, the task is performed in concomitance of the physical effort under different workload intensities. Second, our study includes a test of maximal fatigue capacity and utilize intensities that are relative to each participant's maximum exercise workload. Third, our sample included a sufficient number of both male and female. It should be noted that females are widely underrepresented in this literature (Lambourne & Tomporowski, 2010). The present study, however, suffers from some technical limitations. In particular, an implicit limit of every study concerning free-choices are the instructions that are provided to the participants: there is a delicate balance between letting participants truly choose freely and the experimental requirement of sampling enough data from all possible responses. Another limitation relates to the physiological recordings: arousal data were sampled only few times for each participant to control for heart rate variability, but this aspect was no further analysed. Future studies should overcome this limitation by introducing a continuous recording of physiological data, allowing for a direct link between arousal intensity and the performance at the single trial.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.psychsport.2017.11.012.

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