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Review

The strength model of self-control revisited: Linking acute and chronic effects of exercise on executive functions

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Abstract
Since the 1960's, hundreds of articles have been published on the effects of exercise on cognition and more recently on executive functions. A large variety of effects have been observed: acute or long-lasting, facilitating or debilitating. Several theoretical frameworks have been proposed to explain these effects with plausible mechanisms. However, as yet none of these models has succeeded in unifying all the observations in a single framework that subsumes all effects. The aim of the present review is to revisit the strength model of self-control initiated by Baumeister and his colleagues in the 1990's in order to extend its assumptions to exercise psychology. This model provides a heuristic framework that can explain and predict the effects of acute and chronic exercise on effortful tasks tapping self-regulation or executive functions. A reconsideration of exercise as a self-control task results from this perspective. A new avenue for future research is delineated besides more traditional approaches.

Keywords
Adherence; Effort; Motivation; Pleasure; Positive mood; Resource; Self-regulation; Training; Transfer; Willpower

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1. Introduction

Homo sapiens have always had to cope with stressful environmental and social events that require self-regulation and executive functions, two intricately linked mental functions. For instance, individuals regularly have to change or stop behaviors that would place them at risk for severe injury, health problems, death, group exclusion, or failure to reach a specific goal. Self-regulation refers to psychophysiological processes that enable an individual to guide his/her goal-directed activities over time and across changing circumstances[1]. Executive functions are high-level cognitive functions that subserve and are a prerequisite for self-regulation[2, 3]. According to a well-known and frequently used taxonomy[4], at least three main and elementary components of executive functions can be identified: (1) maintenance and updating of relevant information in working memory, (2) inhibition of prepotent impulses, unwanted and intrusive thoughts, embarrassing emotions, or automatized responses, and (3) mental set shifting also known as cognitive flexibility. Other high-level cognitive processes such as volition and planning[5] and sustained and selective attention[6] have also been considered to be intrinsically linked to executive functions. Self-regulation and executive functions bring into play energetic resources, commonly named effort, in order to meet the demands of a task[7,8]. Cognitive neurosciences have shown that functioning of self-regulation and executive functions are both strongly but not exclusively dependent on the integrity of prefrontal regions[9-11], one of the most extended but vulnerable parts of the Homo sapiens' brain[12,13].The well-functioning of executive functions is generally measured with neuropsychological or cognitive tasks. In order to clarify the terminology used in this article, we name "self-regulation task" an effortful task involving executive functions and prefrontal brain regions.

Considering the prevalence and the salience of executive control in human behavior, it seems important to study factors that impair or improve its functioning. Consistent findings have emerged from the scientific literature over the last 30 years: chronic exercise improves executive functions in children[14], young adults[15], and older adults[16] and slows down the aging process in prefrontal brain regions[17], whereas acute exercise impairs or improves performance in tasks tapping executive functions according to the conditions of execution of the cognitive task[18,19] (while exercising versus just after exercise). Most of these positive or negative effects of exercise have been explained by different theoretical models (e.g., neurotrophic factors hypothesis for chronic exercise[20], hypofrontality hypothesis or catecholaminergic hypothesis for acute exercise[21]). However, none of these current theories unify all of the observations reported above in a single framework that subsumes all effects. The main purpose of this article is to present a theoretical model that establishes a link between acute and chronic effects of exercise on executive functions and proposes alternative but plausible mechanisms to explain the causal relationship between exercise and executive functions. Formalizing heuristic models characterized by a limited number of inter-related variables and a high predictive value is the Holy Grail of empirical science. The model of interest is a new application and extension of an already existing model rather than a completely new model. We will present an argument that Baumeister's strength model of self-control[22-24], revisited from the perspective of exercise psychology, furnishes an adequate theoretical framework to explain and predict effects of acute as well as chronic exercise on self-regulation tasks.

This model, originating from social psychology, resembles classical resource models from cognitive psychology because the main assumption considers that individuals have a limited amount of energetic resources to cope with self-regulation problems. However, it differs from classical models because it is more focused on the delayed consequences of resource depletion on a subsequent self-regulation task than the immediate consequences of dividing resources to perform two tasks at once. We will see later in this article that this specificity of the strength model of self-control opens new perspectives in the comprehension of the exercise-cognition relationship.

The article is divided into six sections including this introductive first section. In Section 2, we present Baumeister's strength model of self-control and its extensions and make a short comparative analysis of this model with more classical cognitive-energetic models. In Section 3, we synthesize the main results concerning the effects of self-control depletion tasks on exercise. In Section 4, we consider some methodological issues related to the study of the exercise–self-regulation relationship, distinguish two types of exercises based upon requirements for self-control resources, summarize the existing data showing an effect of exercise on self-regulation task, and present briefly both the current explanatory mechanisms

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underlying these effects and the alternative explanations in the framework of the strength model of self-control. In Section 5, we consider the possibility to increase the capacity in self-control resources by exercising and cognitive training. Finally, in Section 6, we present some arguments for the interest to strengthen self-control resources in order to increase short-term and long-term adherence processes.

2. The strength model of self-control

Among existing models of self-regulation[25-28], the most currently adapted to health and exercise psychology is Baumeister's strength model of self-control[29]. Self-control is viewed as a limited resource that is depleted when people engage in behaviors that require self-regulation[22, 29]. Self-regulation refers to a psychological function and is defined as "*any efforts undertaken to alter one's behavior*"[30], whereas self-control, colloquially known as willpower, is related to a mental capacity (i.e., a cognitive resource) and defined as "*the exertion of control over the self by the self (…) when a person attempts to change the way he or she would otherwise think, feel, or behave*"[22]. As suggested by Baumeister[31], self-regulation is linked to executive functions but would be only solicited in tasks which require overriding or inhibiting competing behaviors, desires or emotions. Consequently, we can consider that self-regulation and executive functions share effort as a resource to consciously alter behavior (e.g., restraining impulses and resisting temptations) or to successfully perform stressful and/or attention-demanding tasks. In other words, we can consider that mental effort is to executive functions what self-control is to self-regulation. Indeed, the effort mechanism that is a part of Sanders' and Hockey's models presents high similitudes with Baumeister's self-control mechanism.

Baumeister's model conceives self-control as a limited and global resource and explains conditions in which it may fail. Depletion of self-control resources in one domain leads to self-regulatory failure in others. Indeed, the strength model of self-control considers different domains or spheres of self-regulation. A meta-analysis carried out by Hagger et al.[24] reported seven domains in which consequences of self-control depletion had been studied: control of thoughts, control of emotions, control of attention, control of impulses, cognitive performance, choice and volition, and social processing. A possible eighth sphere of self-regulation could be added to this list and studied in the field of exercise psychology: control of effort during exercise.

Baumeister and Vohs[32] identified four main requirements for effective self-regulation: (1) standards, (2) self-monitoring, (3) willpower, and (4) motivation. First, situations and tasks that require self-regulation must be determined by a clear and well-defined standard (i.e., goal, norm, or value). Second, self-monitoring involves comparing the relevant aspect of the self (e.g., desire to regularly practice physical activity although currently sedentary) to the standard (e.g., following the WHO recommendations concerning physical activity). This ability requires evaluating progress toward achieving the standard. Third, changing the self is difficult and requires a capacity-limited resource named self-control or willpower. Following the comparison with the standard, self-control capacity leads either to change the self in order to bring it up to the standard or confirming that it has now been brought into line. Finally, motivation can be considered as the general drive or inclination to reach the goal, adhere to a social norm, or move closer to personal values.[32] Consequently, effective self-regulatory operations are conscious, intentional, goal directed and fueled by available self-control resources.

In order to test the predictions of the strength model of self-control through an experimental approach, social psychologists typically elaborate designs using a self-control depletion protocol[29, 33, 34] (Fig. 1A). According to this protocol, the first act of self-control (task 1) will consume some quantity of this resource, and so the individual will face the second task with a diminished capacity to engage in self-control. The first task is frequently named the depleting self-control task whereas the second one is referred to as the dependent self-control task. A control task, involving a smaller self-regulation component, is used as the first task for another group of participants, and performance measured in the dependent self-control task subsequent to the control task is considered as baseline performance.

Predictions from the strength model of self-control rely on three main hypotheses: conservation, training, and recovery hypotheses[35]. Concerning the conservation hypothesis, a depleted state does not reflect a complete exhaustion of resources. In fact, individuals maintain a minimal level of self-control resources in order to complete eventual future tasks. We will name this psychological limit the 'conservation threshold'. The training hypothesis suggests that people can improve their self-control capacity by engaging in a regular

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program of practice or training on self-control tasks. This hypothesis will be examined more carefully in Section 5. The recovery hypothesis suggests that a period of rest or recuperation will lead to the replenishment of self-control resources[22]. The time course of this recovery process is not very well documented and needs further examination.

According to the conservation hypothesis, individuals usually tend to conserve resources and withhold effort once they start feeling depleted. However, the strength model of self-control considers that the detrimental effect of self-control resource depletion can be reduced or annihilated by acute changes in individual's attitude or emotional state. According to their mental state, individuals can resist the debilitating effects of resource depletion by expending more of the remaining self-control resources. Several acute changes in mental state can lead to improvement in self-control strength and allow individuals to go beyond their usual limits[36-42]. For instance, Tice et al.[36] showed that, after an initial act of self-regulation, participants who experienced a positive mood by watching a comedy video or receiving a surprise gift self-regulated on various tasks as well as non-depleted participants and were significantly better than participants who experienced a sad mood induction, a neutral mood stimulus, or a brief rest period[36]. Other factors, such as motivation and implementation of intentions, would influence self-control very similarly to positive emotion[39-41]. We will be particularly interested by the effect of positive mood on self-control strength because an abundant literature shows that acute exercise increases positive mood[43, 44]. In Section 4.2, we will make a link between positive aftereffects of acute exercise on executive functions and the effect of positive mood on self-control strength. It is time now to see how the strength model of self-control has been applied to the sphere of exercise psychology.

3. Self-control depletion and exercise

Several studies based on the strength model of self-control examined the effects of an exhausting self-regulation task on subsequent exercise. Table 1 synthesizes these studies conducted from 1998 to today. The majority of these studies used the handgrip task as physical exercise. Muraven et al. [34] considered that squeezing a handgrip require self-regulation to make oneself continue squeezing despite muscular fatigue and to overcome the urge to release the grip. As it can be seen in Table 1, the depleting self-control task varied according to the aim of the study and is described in column 2, the dependent self-control task (here, an exercise task) was always carried out immediately or shortly after (less than 10 min) the depleting self-control task, the participants were systematically young adults students, and their physical fitness level was never controlled.

Martin Ginis et al.[45] and Dorris et al.[46] were the first exercise psychologists to use other types of exercise in order to deplete self-control resources. Martin Ginis and collaborators used a high-intensity pedaling exercise on a cycle ergometer whereas Dorris and coworkers used resistance exercises such as press-ups and sit-ups. Both studies confirmed that these categories of exercise also require self-regulation and deplete self-control. In 2012, Englert and Bertrams[47] used two motor skills (basketball free throws and dart throws) as dependent self-control tasks. Their main hypothesis considered that anxiety has a detrimental effect on selective attention, a cognitive function that requires executive control. Self-control would enable an athlete to override the automatic tendency to pay attention to threatening stimuli and instead to focus on other stimuli. Thus self-control should protect anxious individuals from performance decrements. In their first experiment, they showed that the effect of self-control depletion is more debilitating for shooting performance in basketball players who were high in state anxiety. In their second experiment, they showed a detrimental effect of self-control depletion on dart-tossing performance only in the anxiogenous context. State anxiety was varied by manipulating participants' instructions. In order to generate an anxiogenous context, participants were informed that: (1) it was extremely important to perform as well as possible; (2) it should not be a problem for a normally gifted human being to perform at a high level; (3) their performance would be compared with other participants' performances; and (4) they would receive personal face-to-face feedback from the experimenter. More recently, McEwan et al.[48] also used a dart-throwing task in order to examine whether depleted self-control strength impairs an individual's ability to perform subsequent sports tasks that require self-regulation. In this study it is important to note that the dart-throwing task involved a clear executive component: participants were instructed to throw when they saw a green light flash and not to throw when they saw a red or yellow light flash. As expected, participants in the self-control depletion condition had poorer mean accuracy (the distance in centimeters between where each toss landed and the

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center of the bulls-eye) than control condition participants. Future experiments on this topic will have to examine the possibility of including an executive component in the exercise; for instance including orienteering and planning during walking or jogging. Such an inclusion provides one way among others to increase the amount of self-control required to perform the exercise (Table 2).

Other experiments are now necessary to define more precisely how the characteristics of exercise impact the depletion of self-control resources. This is important for two main reasons: (1) to allow for a more accurate definition of the experimental conditions leading to detrimental effects of exercise on executive functions and self-regulation; (2) to better understand the type of exercise that can be used to train self-regulation, strengthen self-control and increase adherence to exercise (Section 6). Table 2 includes several exercise parameters that could be taken into account to increase or decrease the amount of self-control resources required to exercise. All these parameters have to be manipulated as independent variables in protocols exploring the exercise – self-regulation relationship, and the level of each variable has to be varied to explore the range of its propensity to deplete self-control resources.

4. Exercise and executive functions: existing data and explanatory mechanisms

The variety of exercise effects on executive functions depends on several protocol-related variables that have been clearly identified by exercise psychologists[49-51]. One of the most important variables is the time scale of the effect: acute effects of exercise are immediate and transient state changes induced by a single bout of exercise whereas chronic effects are cumulative and durable dispositional changes induced by the repetition of bouts of acute exercise several times a week over a period of weeks, months, or years. When applying this distinction to executive functions, acute effects correspond to short-term and short-lived improvement or impairment of performance in cognitive tasks tapping executive functions whereas chronic effects correspond to long-term and stable improvement of performance in the same cognitive tasks.

The second variable concerns the type of protocol used to study acute effects of exercise on executive functions and more particularly the temporal arrangement between exercising and performing a cognitive task. In “concomitance protocols” (in-task exercise), the cognitive task is performed during exercise whereas in “sequence protocols” (off-task exercise), the cognitive task is performed just after the end of exercise or later (Fig. 1B and 1C). These two types of protocols provide contradictory results that can be explained within the framework of the strength model of self-control.

The third variable that determines the direction and the effect size of exercise on executive functions is the degree of effort or self-control resources needed to perform the exercise .We consider a continuum of exercise from exhausting exercise consuming a large amount of self-control resources and requiring sustained effort (e.g., ultra-marathon, ironman triathlon) to low effort exercise performed at preferred and comfortable intensity and duration (e.g., walking or jogging at preferred speed). Table 2 presents the main characteristics of effortful and low effort exercises. Performing exercise can be a very pleasant or a very hard experience dependent upon intensity, duration, mode, and past experiences of the exerciser. Continuing an exercise despite pains in some parts of the body, unfavorable conditions of practice (e.g., heat or cold) and/or a lack of motivation to practice implies repressing the desire either to stop exercising or to lower the intensity of the exercise. Inhibition of intentions requires executive control and self-regulation; the harder the exercise, the more self-control resources are needed to complete it. The amount of available self-control resources is limited and we will see later that depleting these resources during effortful exercise may influence subsequent performance in a task also requiring self-control.

In the following sub-sections we will present three sets of data published in the literature: (1) negative and positive effects of acute exercise on executive functions when the cognitive task is performed during exercise, (2) negative and positive effects of acute exercise on executive functions when the cognitive task is performed just after exercise, and (3) positive effects of chronic exercise on executive functions after several weeks of training. We only examine studies published in journals indexed by the Institute for Scientific Information (ISI) showing detrimental or facilitating effects of exercise on executive functions according to the three protocol-related variables presented above. We made the choice not to include “null effect” studies because the sample size used in this type of study is generally low and consequently the likelihood of accepting the null hypothesis is high. After a careful examination of the methodology section of each selected article, we only include studies using appropriate dependent variables to assess executive functions and showing positive or negative effects of exercise on these behavioral indices of performance.

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4.1. Negative and positive effects of acute exercise in concomitance protocols

In this sub-section, we focus the review on studies that showed detrimental and facilitating effects of acute exercise on executive functions while exercising. We also include studies that observed a shift to a less effortful strategy enabling performance of the cognitive task during exercise. Hockey[8] showed that this type of compensatory tradeoff reflects a latent breakdown in performance and the manifestation of a self-regulation process. Few studies have used self-regulation tasks in concomitance exercise protocols. The majority of these studies showed a detrimental effect of in-task exercise on executive functions and, to our knowledge, only three showed a facilitating effect of acute exercise on executive functions (Table 3).

In contrast to the limited study of executive function during exercise, studies reporting on the positive effects of acute exercise on speed of information processing measured through reaction time are very common[18, 19, 49, 50]. However, the data showing a positive effect of in-task exercise on cognitive tasks including only a small executive component (e.g., two-choice reaction time task with a compatible stimulus-response mapping) will not be discussed in this review. Measuring the well-functioning of executive functions is a complex problem[52]. The "task impurity" problem is one of the most important obstacles that psychologists have to address to obtain a satisfying assessment of executive functions. Tasks that tap on executive functions generally stress practically all cognitive systems in addition to the executive[53]. In order to determine whether deterioration or improvement of performance strictly affects the executive system, one must be able to identify practically all other non-executive contributions to the task and use pertinent indices of performance specifically reflecting the functioning of executive control. For that reason, it is very important to analyze the scientific literature according to the cognitive tasks and the indices of performance used by the researchers to examine the exercise–self-regulation relationship. Three main pieces of information are displayed in Table 3: (1) the self-regulation task used in the experiment, (2) the executive function(s) tapped by the self-regulation task, and (3) the indices of performance selected to measure executive functions. Four additional pieces of information are also displayed in Table 3 because they are useful in the framework of the strength model of self-control: intensity and duration of exercise and age and physical fitness of participants. We can expect that the higher the intensity and duration of the exercise, the higher the amount of self-control required to perform the exercise. In the same way, we can also expect that high-fit individuals use less self-control resource than low-fit participants for the same intensity of exercise. Finally, because aging studies show that older adults use more executive control to walk[54], we can expect that older participants will require higher self-control resources to perform a physical exercise involving balance control.

Detrimental effects of in-task exercise on cognitive functions have been generally explained by competition of resources between performing the cognitive task and maintaining the exercise. According to cognitive-energetic models[49], we can consider that exercise and cognition share a common capacity-limited reservoir of voluntary attention or mental effort. A more recent neurocognitive model (the reticular-activating hypofrontality model) considers that in the case of locomotion, the brain must shift limited metabolic resources (mainly glucose) to neural structures that sustain the movement, which leaves fewer resources for brain regions computing functions that are not critically needed at the time, for instance executive functions[21]. Whatever the type of limited resources, in both these theoretical models, the core idea is the same: performing a self-regulation task and maintaining exercise simultaneously requires dividing available resources between the two tasks. The main difference between cognitive-energetic models and the reticular-activating hypofrontality (RAH) model is the nature of resources that have to be divided between exercise and the cognitive task: mental effort in the case of cognitive-energetic models and brain glucose in the case of the RAH model. Another difference is the way to allocate resources to executive functions and/or exercise. In cognitive-energetic models, the allocation policy is under the control of an attentional supervisor that selects a mode of regulation among several available strategies[8]: either to stop or decrease intensity of exercise in order to perform the cognitive task without any decrement of cognitive performance, to stop performing the cognitive task in order to maintain the same intensity of exercise, or to maintain both exercising and performing the cognitive task at the risk of impairing both of them[55, 56]. In the RAH model, the allocation of metabolic resources to brain regions is not under the control of any attentional supervisor, but is conceived of as a basic tradeoff process. Maintaining bodily motion requires, on the one hand, a substantial allocation of metabolic resources to motor, sensory, and autonomic brain regions that control and

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underlie the movement and, on the other hand, a simultaneous down-regulation of other brain regions like the prefrontal cortex, which are not necessary for the execution of automatized movements and can decrease their efficiency. The allocation of brain glucose to active brain regions involved in maintaining exercise follows the biophysical principle of neurovascular coupling[57]. The neural activation of brain structures involved in the execution of exercise leads to an increase of cerebral blood flow (CBF) in these regions. By contrast, a significant decrease in neural activation in other brain regions not involved in the movement results in a decrease of CBF in these regions. In other words, neural activation of brain structures involved in the execution of exercise would be intrinsically coupled to a deactivation of prefrontal cortex. The RAH model does not deny that each individual can decide to stop exercise and/or the cognitive task at any time he/she wants, but it assumes that the down-regulation of prefrontal areas during exercise is not a voluntary process but an evolutionary pre-wired mechanism.

The strength model of self-control was not directly focused on dual-task resource conflicts and tradeoffs but rather on the postponed consequences of depleting self-control resources. However, it would be very interesting to extend the strength model to multi-tasking and dividing attention situations because, as we mentioned above, cognitive-energetic models and the strength model share very similar theoretical bases. We can add an additional assumption to the strength model: when an individual has to perform two or more self-regulation tasks at the same time, he/she has to divide his/her self-control resources between the several tasks considering the limited capacity of these specific resources. Consequently, the more an exercise session requires self-control resources, the more a self-regulation task that is simultaneously performed will be impaired as long as available self-control resources at that time are exceeded by task demands. As expected a majority of nine studies out of 12 showed deleterious effects of in-task exercise on executive functions. Only three studies showed positive effects. The results of these three studies can be explained by a facilitating effect of catecholamines on executive functions combined with a probable too short and too light exercise to produce negative effects.

4.2. Negative and positive effects of acute exercise in sequence protocols

Contrary to the negative effects observed in concomitance protocols, there is currently no plausible and satisfying rationale explaining both negative and positive effects of acute exercise on a subsequent cognitive task tapping executive functions. Cognitive-energetic models can predict positive effects when the cognitive task is performed immediately after exercise. The improvement of performance is generally explained by an increase of arousal and activation induced by exercise. However, according to Sanders' model[7], these two energetic mechanisms facilitate sensory and motor processes but not executive functions. Cognitive energetic models can also predict negative effects when a sub-optimal state is induced by too intense or too long exercise that depletes effort. In that case, Sanders' model predicts a detrimental effect of exercise on decision-making processes, a stage of processing that requires executive functions. This prediction from the Sanders' model is very similar to the prediction that will be made from the Baumeister's model. However, to our knowledge, this prediction from the Sanders' model has never been tested and the time course of the exhaustion of effort when continually loaded never properly examined. Table 4 presents studies that reported a positive effect of acute exercise on executive functions in sequence protocols with the same pieces of information than inTable 3.

By contrast to in-task exercise protocols, positive effects of acute exercise are commonly observed in off-task exercise protocols. As we will see further, we found only two studies showing a detrimental effect of off-task exercise on tasks clearly involving executive functions (see further in this section). We also found two studies showing a detrimental effect of acute exercise on cognitive tasks tapping more indirectly executive functions. The first study showed a clear detrimental effect of a marathon race on explicit memory processes[58]. The second study showed that pedaling on a cycle ergometer at a maximal level of effort for 6 min impaired performance of the divergent thinking task (i.e., alternate uses task) in both athletes and non-athletes and impaired performance of the convergent thinking task (i.e., remote association task) only in non-athletes[59].

The strength model of self-control has been specifically conceived to predict sequential effects. The first variable that must be taken into account in considering the effects is the level of self-control resources required to maintain exercise. If the exercise requires a high level of self-control resources (e.g., a long vigorous and uncomfortable exercise), the strength model predicts that a subsequent task also tapping self-

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regulation functions will be impaired, while a subsequent cognitive task that does not involve self-regulation will not be impaired. Conversely, if the exercise requires a low level of self-control resources (e.g., a short jogging bout at a freely chosen speed), the strength model predicts that a subsequent cognitive task will not be impaired.

As yet and to our knowledge, exercise has been manipulated in order to purposefully induce a depletion of self-control resources and test the effect of acute exercise on a subsequent self-regulation task in only two experiments. The first study was published by Gröpel et al. in 2014[60]. In their first pilot experiment, these authors used 15 min of strenuous resistance exercises at maximal intensity as the depleting self-control task and the d2 test[61] as the dependent self-control task in semi-professional athletes. They considered the hypothesis that people differently allocate self-control resources once they start feeling depleted according to their personality profile. According to the action control theory[62], action-oriented individuals respond to increase in demands with decisiveness and initiative whereas state-oriented individuals sustain and preserve their current mental and behavioral states in the same situation. The detrimental effect of the depleting self-control task was only observed in state-oriented participants but not in their action-oriented counterpart meaning that action-oriented athletes continued to invest self-control resources when they felt depleted whereas state-oriented athletes did not. Thus, a strenuous exercise can lead to detrimental effects on self-regulation tasks in state-oriented people. The second study was conducted in our laboratory and is currently unpublished. An incremental maximal running task was used as the depleting self-control task, a self-paced jogging task was used as the control condition, and a modified version of the Stroop task was the dependent self-control task. The dependent self-regulation task tapped two executive functions: inhibition of a prepotent response and cognitive flexibility. We observed a significant increase of errors for incongruent and switching trials (tasks expected to require self-control) in the depleting condition by comparison to the control condition, but no change in mean reaction time. This last result means that the increase in error rate observed immediately after an incremental running exercise was not a strategy used by the participants to react more rapidly. The results of these two experiments validate predictions of the strength model of self-control and show that negative aftereffects of exercise can be obtained with highly depleting self-control exercises. These two studies open a new research avenue in exercise psychology concerning possible negative effects of acute exercise on cognition. However the results need to be replicated with other types of depleting self-control exercises and miscellaneous subsequent self-regulation tasks in order to demonstrate their generalization to all the spheres of self-regulation.

As it was suggested previously in this paper, exercise may have a detrimental or a facilitating influence on self-regulation tasks according to its characteristics. On the one hand, effortful exercises (Table 2) lead to self-control depletion and have a detrimental influence on a subsequent self-regulation task. On the other hand, we suggested in Section 2 that a state of positive mood allows individuals to resist the detrimental effect of resource depletion by expending more of the remaining self-control resources. Considering that larger effect size on positive mood is consistently observed immediately after acute exercise for doses ranging from 10–30 min low intensity exercise to 20–30 min high intensity[44], we can make here the hypothesis that if exercise increases positive affect, it can have a facilitating effect of self-control strength and help individuals to go beyond their usual limits. Fig. 2 illustrates these two opposite influences. Fig. 2A shows how the comparison of the depleting self-control condition and the control condition can lead to a decrease in performance of the dependent self-control task. Fig. 2B shows how the decrease of the usual conservation threshold induced by a shift to positive mood can lead to cancellation of the detrimental effect of self-control depletion.

Fig. 2 also demonstrates that this change in conservation threshold level cannot explain a real improvement of performance in self-regulation tasks. The facilitating effect described by Baumeister and his collaborators must be only viewed as a compensatory mechanism allowing to restore a baseline level of performance. However, several studies conducted by Isen and her collaborators clearly showed that positive affect leads to real improvement of performance in creativity[63,64] and decision-making[65], two cognitive functions involving executive control. In addition, studies reported in Table 4 show clear improvements of performance in self-regulation tasks induced by acute exercise. Presently, no valuable explanation can account for these positive aftereffects of acute exercise on self-regulation tasks. In order to explain these improvements of performance in self-regulation task we need to extend the strength model of self-control by adding a new

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hypothesis that we name the overcompensation hypothesis. As muscular strength can be increased during an isometric contraction by recruiting more motor units (principle of spatial recruitment[66]), self-control strength could be increased by recruiting more neuronal units involved in pre-frontal areas. Such a mechanism has already been observed in several occasions, for instance when older adults show greater extent of brain activation than younger adults for similar objective levels of difficulty[67,68]. Moreover, some studies showed that older adults had better performance than young adults in sustained attention tasks involving executive functions associated with more extended activation in prefrontal areas[69]. This extension of activation to additional neuronal units involved in self-regulation would be possible under certain circumstances such as an increase in positive emotion or an increase in motivation. We named this mechanism "overcompensation" to underline the fact that this mechanism allows to go beyond a simple compensation such as a decrease of the conservation threshold described in Fig. 2B.

Another mechanism can also explain a positive effect of acute exercise and positive emotion on executive functions: the dopaminergic hypothesis. We do not develop this hypothesis here because it is not related to the strength model of self-control but shortly it considers that the increase in brain dopamine following acute exercise or positive emotion modulates prefrontal networks involved in self-regulation and enhances their processing effectiveness. The overcompensation hypothesis and the dopaminergic hypothesis are not antagonistic and may act in convergence. These two hypotheses could be tested with mediational analyses and brain imagery.

According to cognitive energetic models, the intensity of the arousing stimulation induced by acute exercise is the most important dimension that must be taken into account in order to facilitate information processing or compensate for a sub-optimal state of energy. In addition, as mentioned above, only sensory, perceptual and motor processes could benefit from an increase in arousal or activation[49]. By contrast, the strength model of self-control considers the positive valence of emotions as the most important stimulation dimension that must be taken into account to enhance self-control and effort and consequently improve executive functions. The two explanations of the positive effects of acute exercise on cognitive performance in tasks carried out immediately after exercise (increase in arousal/activation *vs.* increase in positive mood) could be synergistic rather than in opposition. A cognitive task generally involves several components and taps several cognitive and sensori-motor processes. We can thus hypothesize that sensory and motor components of the task can be facilitated by an increase in arousal and activation induced by exercise while executive components of the task can be facilitated by the positive emotions induced by exercise. Two different experimental approaches could test this hypothesis: (1) using a hierarchical regression approach determining the percentage of variance in self-regulation performance explained by each of the two mechanisms; (2) using a cognitive task that allows for the distinction between the different task components with different indices of performance (e.g., a fractionated choice reaction time task including the neutral and the incongruent conditions of the Stroop Task).

4.3. Positive effects of chronic exercise

Positive effects of chronic exercise or regular physical activity on executive processes are certainly the best documented phenomena of exercise psychology concerning the exercise-cognition relationship. Several narrative and meta-analytic reviews have been carried out on this topic[16, 51, 70-73]. Two populations have been the preferential targets of most of the studies interested in the prophylactic effects of chronic exercise on cognition: children with reference to the improvement of academic achievement and older adults in order to slow-down the aging process or compensate for cognitive declines due to normal or pathological aging. The moderating effect of physical activity on cognitive and brain health has been studied with the help of epidemiological, longitudinal, cross-sectional, and interventional protocols.

Because of the limitations inherent in cross-sectional and epidemiological studies, we made the choice to focus this review on interventional studies that use a randomized control trial (RCT) to test a causal effect of chronic exercise on executive functions. The number of intervention studies showing a positive effect of a physical activity program on executive functions is so large (more than 20) that we will not report them in a table as in previous sections. We invite the reader to consult recent reviews and meta-analyses on this topic[60, 72,73]. Globally, the size of the effect is small to moderate and can be influenced by several moderators such as the duration of the program (number of weeks), the frequency of physical activity sessions (number of sessions per week), the duration of the sessions (number of minutes from the warming-up to the cooling-

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down phases), the intensity of exercise during the main part of each session, and the characteristics of participants (gender, age, level of frailty, genetic polymorphisms).

Since the beginning of the 21st century, the neurotrophic hypothesis has been commonly proposed to explain the positive effects of chronic exercise on executive functions and other cognitive functions such as episodic memory. This hypothesis considers that chronic exercise leads to a cascade of biological mechanisms such as increasing brain availability of several classes of growth factors (e.g., brain-derived neurotrophic factor; BDNF), enhancing brain plasticity and vascular function (e.g., angiogenesis, neurogenesis, and synaptogenesis), and improving brain integrity and efficiency of neural networks involved in executive functions[20]. However, a series of alternative more psychological hypotheses can also explain, at least in part, the positive effects of chronic exercise on self-regulation and executive functions. This series of three hypotheses is in line with the strength model of self-control and all three have been already validated. The first hypothesis is that exercising requires self-control resources to manage the discomfort and sometimes the pain that people experience during exercise and that this requirement is greater for people with a low physical fitness. The second hypothesis (training hypothesis already discussed in Section 2) is that training the self-regulation function will lead to an increase of self-control capacity (i.e., amount of available resources). The third hypothesis is that the benefit in self-control resources obtained through physical exercise can be transferred into the cognitive domain by facilitating self-regulation. We do not pretend that this series of self-control hypotheses explains the majority of the variance of executive task performance due to chronic exercise. Our view is that it can explain a significant part of the variance in addition to the neurotrophic hypothesis. The interest of these three hypotheses is supported by their extension in the domain of exercise adherence as we can see in Section 6.

5. Exercising self-control

Baumeister and co-workers have often compared self-control to a muscle[23]. This analogy comes from the observation that self-control performance declines after an initial utilization that depleted self-control resources (Fig. 2A), just as a muscle gets tired from exhausting exercise that depletes phosphagen resources. In addition, just as exercise training can make muscles stronger, there are several arguments for an improvement of self-control strength following regular self-control exertions[74].

According to Oaten and Cheng[75], chronic effects of self-regulation training programs designed to increase regulatory strength lead to improvement in self-regulatory capacity, i.e., the amount of available self-control resources (capacity hypothesis). This change in resource availability can be conceived of as being more durable and similar to a change in muscular phosphagen reserve after strength training. Baumeister and co-workers proposed an alternative explanation: a durable and dispositional change in the participant's personality enabling him/her to go beyond his/her usual limits[23] (persistence hypothesis). These two hypotheses are derived from the strength model of self-control and come in addition to the three initial hypotheses presented in Section 2. The persistence hypothesis is very similar to the transitory change in conservation threshold induced by a shift to a positive mood or an increase in motivation (see Sections 2 and 4.2). However, after self-control training program the change in conservation threshold would be durable instead to be transient. The capacity hypothesis of self-control strength improvement after self-control training is illustrated on Fig. 3. It would be difficult to test between the capacity and the persistence hypotheses because they both predict the same changes in behavioral performance. A first step could be to formalize these two hypotheses at the neurophysiological level but that challenge is beyond the scope of this paper.

As yet, few studies have demonstrated that programs of self-regulatory exercises over several weeks lead to a decrease of the self-control depletion effect[74]. One of these studies is particularly interesting for the purpose of the present article because the researchers used a 2-month physical activity program as self-control training[75]. Tailored programs included weightlifting, resistance training, and aerobics exercises. At the pre-intervention session, most participants showed the self-control depletion effect quite clearly, but after 2 months of adhering to the exercise regimen, the effect was substantially reduced. More crucially, adherence to the exercise program was also beneficial to self-control in other spheres; for instance: reducing participants' cigarette smoking, alcohol use, and caffeine consumption. The results of the intervention studies listed by Baumeister and collaborators[74] suggest that training self-regulation operates by increasing a general core capacity and that improving self-regulation in one sphere enables an individual to become

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better at self-regulating in other spheres. More recently, a review conducted by Berkman and colleagues examined the possible neurophysiological mechanisms underlying these training effects[76]. They presented several empirical arguments showing that the right inferior frontal gyrus is a key component in the network that ultimately inhibits behavior in the service of top-down goals, making this region an excellent candidate target for self-control training interventions. Two important ideas emerge from Baumeister's review[74]: (1) self-regulation is trainable, and particularly through physical exercise programs; (2) gains in self-control strength acquired in one sphere of self-regulation are transferable to other spheres.

These two ideas strongly resemble isomorphic hypotheses made in cognitive psychology concerning executive functions. There has recently been a significant interest in whether executive functions can be improved via cognitive training and mental stimulation in different populations[77-81]. Several narrative and meta-analytic reviews have assessed the effectiveness of these training methods with a specific interest in executive functions[82-84]. Although there is no doubt that executive functions such as attentional control, cognitive flexibility or working memory capacity can be improved through training, the extent to which these improvements generalize and show positive transfers to everyday life activities is still strongly debated. Concerning the effectiveness of exercise training on the improvement of executive functions, we invite the reader to return to Section 4.3.

6. Strengthening self-control: a way to improve adherence to exercise

As defined earlier, self-control is the self's capacity for altering its own behaviors, i.e., durably adjusting oneself to desirable outcomes. For instance, in order to become a healthy person, I can decide to exercise regularly, to eat more vegetables and fruits, and to stop smoking. All these target behaviors need modification of the self and are effort consuming. A first difficulty is to engage oneself in these new behaviors. A second difficulty is to durably maintain these behavior adjustments and make them habits. In the first case, an abundant literature has been published in psychosocial research[85-88]. For instance, the transtheoretical model of behavior change demonstrated that the decision to engage in exercise is based on cognitive factors like weighing pros and cons, appraising personal capabilities, or evaluating sources of support[85,86]. Another, still-under-appreciated possibility is that these decisions are influenced by affective variables such as whether previous exercise experiences were associated with pleasure or displeasure[43]. However, interventions based on the transtheoretical model and similar models aiming to increase the maintenance of the new healthy behavior (i.e., to remain physically active) failed to effectively change behaviors in the long term[89,90]. Adherence to new behaviors requires the use of various effort consuming self-regulatory strategies (e.g., inhibiting a pre-potent unhealthy habit or planning actions). Consequently, both adoption and maintenance of a new behavior draw on self-control resources. Because adherence to healthy behaviors is an important health-related issue, research programs are designed in order to improve adherence to these behaviors. Specifically, intervention-based programs related to the strength model of self-control propose some interesting directions in studying the adherence process[91,92] Among the main self-regulation-based intervention programs, the use of volitional components through goal setting, self-monitoring, formation of action plans, and recall of positive experiences has been shown to be effective to strengthen self-regulation[93-95]. Despite interesting results concerning the effect of such interventions on the adoption of health behaviors[92,96], very little information is given concerning the effectiveness of these interventions on long-term changes; in other words, can we hypothesize a chronic effect of exercising self-control on adherence behaviors?

As demonstrated earlier, self-regulation and executive functions are closely related and share effort as a resource to alter behavior. As suggested by Muraven and Baumeister[22], who often restricted self-regulation to its inhibitory component, refraining from a behavior requires the expenditure of resources that are depleted afterward. For instance, inactive individuals who begin a physical activity program must continually reinitiate the new behavior of being active and may be helped by continuing to think about the benefits of exercising and inhibiting the comfortable project to stay inactive on the sofa. However, behavioral change cannot be restricted to refraining from a behavior, but as a complete reframing of behavior that requires other higher-level cognitive functions such as planning and retrospective memory. For instance, becoming active requires planning time and location of physical activity sessions and remembering when and where to practice. All these cognitive functions solicit self-control resources. Consequently, by trying to maintain their exercise adherence, individuals deplete their resources in self-control. However, as

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reported in Section 4.3, positive effects of chronic exercise or regular physical activity on executive processes are now well-established, and we can suggest that by strengthening the self-control resources by the means of exercise, individuals are more willing to exert effort in order to maintain their exercise adherence.

No study has examined the effects of training self-control on adherence process except indirectly through correlational studies. For instance, in an exercise adherence study, McAuley et al.[97] examined the relationship between self-regulation, executive functions and adherence calculated by the percentage of attendance at exercise sessions. They reported that inhibitory processes and information processing speed were more important for adherence than cognitive flexibility and concluded that individuals who are able to inhibit habitual responses are more likely to adhere to an exercise program. Similar results were obtained with medication adherence with authors reporting that impairment in executive functions was related to poor adherence[98,99]. To sum up, it will be appropriate to progressively introduce exercises requiring more and more self-control resources but never at the cost of stopping the activity. In other words, it is our work to help individuals to adhere to exercise that develops self-control resources. This process may become a virtuous circle, self-control exercises leading to more self-control resources and consequently more adherence and so forth.

7. Conclusion

The aim of this review was to propose a new application of the well-known and often-used "strength model of self-control" initiated by Baumeister and his colleagues in the end of the 20th century in order to reexamine a large corpus of data from exercise and cognitive psychology. The main ideas are that detrimental effects of acute exercise can be explained by the limited capacity of self-control resources, improvements of performance in self-regulation tasks observed after acute exercise by an increase in positive mood that extend the prefrontal areas activated to succeed in self-regulation, and positive effects of chronic exercise by a strengthening of self-control capacity. This approach leads us to reconsider exercise, not only as a physiological stimulation that enables increases in cardiovascular fitness or muscular strength, but also as a psychological stimulation that allows strengthening self-control ability and improvement of executive functions. A new avenue of research is now opened to exercise psychologists in order to explore all the dimensions of exercise that must be taken into account to vary the amount of self-control required to perform the exercise. It will be interesting to examine the time course of the restoration curve of self-control resources once they were depleted, test the effectiveness of physical activity programs combining both exercises that elicit positive emotions and self-control training exercises to increase exercise adherence and the core ability to self-regulate.

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Table 1: Studies showing a detrimental effect of self-control depletion task on subsequent physical exercise

Reference	Self-control depletion task	Physical exercise	Time after the first self-regulation task	Characteristics of participants
Muraven et al. (1998)[34] – Exp. 1	Controlling emotional response while watching an upsetting movie	Maintaining handgrip as long as possible	Time to complete the BMIS	Young adults, psychology students
Ciarocc et al. (2001)[100] – Exp. 2	Ignoring (silence condition) a fellow participant and refusing all conversation	Maintaining handgrip as long as possible	Time to complete eight items of the PANAS	Young adults, undergraduate psychology students
Vohs et al. (2005)[101] – Exp. 2	Presenting oneself contrary to social norms	Maintaining handgrip as long as possible	Immediately	Young adults, undergraduate students
Muraven and Shmueli (2006)[102]– Exp. 1	Overriding an urge to drink produced by exposure to a neutral or tempting cue	Maintaining handgrip as long as possible	Time to complete three questionnaires	Young adults, social drinkers
Tice et al. (2007)[36] – Exp. 3	Suppressing the thought of a white bear	Maintaining handgrip as long as possible	Time to complete the BMIS	Young adults, psychology students
Alberts et al. (2007)[37] – Exp. 1	Solving as many easy or difficult labyrinths as possible	Maintaining handgrip as long as possible	Time to complete the BMIS and to read 25 sentences priming persistence or not	Young adults, undergraduate students
Alberts et al. (2007)[37] – Exp. 2	Calculating and naming the sum of two-digits numbers while distracted by interfering stimuli	Maintaining handgrip as long as possible while submitted to a persistence or neutral prime	Time to complete the BMIS	Young adults, undergraduate students
Martijn et al. (2007)[103]	Solving as many easy or difficult labyrinths as possible	Maintaining handgrip as long as possible	Time to complete a priming text-reading task including detection of five words that did not fit in the context	Young adults, undergraduate students
Bray et al. (2008)[104]	Modified Stroop Task	Maintaining an isometric handgrip contraction of 50% of MVC	Time to complete the BMIS	Young adults, sedentary university students
Alberts et al. (2008)[38]	Lifting a 1.5-kg weight as long as possible	Lifting a 1.5-kg weight as long as possible	Time to complete a fatigue scale and the	Young adults, psychology students

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		simultaneously or not with a counting task	BMIS	
Martin Ginis and Bray (2010)[45]	Modified Stroop task	10 min pedaling on a cycle ergometer at a self-determined RPE of 5	Time to complete three manipulation check items, the BMIS and an exercise planning task	Young adults engaged in no more than two sessions of exercise per week for 30 min or more at moderate intensity over the past 6 months
Dorris et al. (2012)[46] – Exp. 1	Counting back from 1000 in 7-s whilst performing a balancing task	Series of press-ups as long as possible	1 min	Young adults, competitive rowers
Dorris et al. (2012)[46] – Exp. 2	Counting back from 1000 in 7-s whilst performing a balancing task	Series of sit-ups as long as possible	1 min	Young adults, rugby and hockey players
Englert and Bertrams (2012)[47] – Exp. 1	Omitting letters “e” and “n” while transcribing a neutral text	Performing 10 basket-ball throws	Time to complete a 3-item manipulation check	Young adults, amateur male basketball players
Englert and Bertrams (2012)[47] – Exp. 2	Omitting letters “e” and “n” while transcribing a neutral text	Performing nine dart throws in an anxiogenous context	Time to complete a 3-item manipulation check and the PANAS	Young adults, university students
McEwan et al. (2013)[48]	Modified Stroop Task	Dart-tossing task	Time to complete three manipulation check items, the BMIS and an exercise planning task	Young adults
Goto and Kusumi (2013)[39]	Stroop Task	Maintaining an isometric handgrip contraction of 50% of MVC	Immediately	Young adults, university students
Chow et al. (2013)[105]	Emotion suppression task	Maintaining handgrip as long as possible	Immediately	Young adults, undergraduate students

Abbreviations:MVC = maximum voluntary contraction; BMIS = brief mood introspection scale[106]; PANAS = positive and negative affect schedule[107]; RPE = rate of perceived exertion[108]

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Table 2: Main characteristics of effortful and low effort exercises

Exercise parameters	Effortful exercise	Low effort exercise
Intensity	Vigorous to maximal	Light to moderate
Duration	Long to very long	Short to moderate
Comfort	Uncomfortable	Comfortable
Pain	Painful	Painless
Pleasure	Unpleasant	Pleasant
Intrinsic motivation to exert	Forced	Freely chosen
Load of the executive control component	Heavy	Light

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Table 3: Studies showing a negative or a positive effect of acute exercise on performance of cognitive tasks tapping executive functions in concomitance protocols.

Reference	Direction of the effect	Task	Executive functions	Indices of performance	Exercise parameters	Characteristics of participants
Dietrich and Sparling (2004)[109] – Exp. 1	Negative	Wisconsin Card Sorting Task	Switching	Error rate	45 min pedaling on a cycle ergometer or running on a treadmill at 75% HR_{max}	Young adults regularly engaged in endurance training
Dietrich and Sparling (2004)[109] – Exp. 2	Negative	Paced auditory serial addition task	Inhibition of a verbal response and updating of WM	Error rate	65 min running on a treadmill at 75% HR_{max}	Young adults, endurance runners
Pontifex and Hillman (2007)[110]	Negative	Ericksen flanker task	Inhibition of a prepotent response	Error rate	6.5 min pedaling on a cycle ergometer at 60%HR_{max}	Young adults, 35.8 mL/min/kg for females and 42.7 mL/min/kg for males
Audiffren et al. (2009)[111]	Negative	Random number generation task	Inhibition of counting	TPI, run	35 min pedaling on a cycle ergometer at 90%VT	Young adults, 31.39 mL/min/kg for females and 38.67 mL/min/kg for males
Davranche and McMorris (2009)[112]	Negative	Simon Task	Inhibition of a prepotent response	Interference cost	30 min pedaling on a cycle ergometer at 50% MAP	Young adults, 42 mL/min/kg for females and 48 mL/min/kg for males
Del Giorno et al. (2010)[113]	Negative	Contingent continuous performance task– Wisconsin Card Sorting Task	Inhibition of a prepotent response – Switching	False alarm rate -total errors, Perseverative errors, Unique errors	25 min pedaling on a cycle ergometer at 75%VT or 100% VT	Young adults, 41.6 mL/min/kg for females and 50.3 mL/min/kg for males
Labelle et al. (2013)[114]	Negative	Modified Stroop Task	Switching	Error rate	6.5 min pedaling on a cycle ergometer at 80%PPO	Two groups of older adults, 50.62 and 38.33 mL/min/kg

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Wang et al. (2013)[115]	Negative	Wisconsin card sorting test	Switching	Number of conceptual-level responses, number of categories completed, number of perseverative errors	40 min pedaling on a cycle ergometer at 80%HRR	Four groups of young adults, 5521.29 METs/week in average
Labelle et al. (2014)[116]	Negative	Modified Stroop task	Switching	Error rate	6.5 min pedaling on a cycle ergometer at 60% and 80%PPO	Two groups of young adults, 50.62 and 38.33 mL/min/kg, and two groups of older adults, 33.42 and 23.67 mL/min/kg
Pesce and Audiffren (2011)[117]	Positive	Global / Local task	Switching	Specific switch cost	8-12 min pedaling on a cycle ergometer at 60% HRR	Two groups of young adults (elite competitive *vs.* club-standard athletes),and two groups of older adults (same subdivision)
Lucas et al. (2012)[118]	Positive	Modified Stroop task	Inhibition of a prepotent response	Reaction time	8 min pedaling on a cycle ergometer at 30% and 70%HRR	Young adults, 32 mL/min/kg and older adults, 24 mL/min/kg
Martins and Kavussanu (2013)[119] – Exp. 1	Positive	Paced auditory serial addition task	Inhibition of a verbal response and updating of WM	Correct response rate	8 min pedaling on a cycle ergometer at moderate intensity (60-180 W)	Two groups of young adults regularly engaged in exercise training

Abbreviations: MAP = maximum aerobic power; HR_{max} = maximum heart rate; HRR = heart rate reserve; PPO = peak power output; Run = run score; TPI = turning point index; VT = ventilatory threshold; WM = working memory.

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Table 4: Studies showing a positive effect of acute exercise on performance of cognitive tasks tapping executive functions in sequence protocols

Reference	Task	Executive functions	Indices of performance	Exercise parameters	Time after exercise	Characteristics of participants
Hogervorst et al. (1996)[120]	Stroop Task	Inhibition of a prepotent response	Time to complete the task	60 min pedaling on a cycle ergometer at 40%MWC	Immediately	Young adults, triathletes and competitive cyclists
Sibley et al. (2006)[121]	Stroop Task	Inhibition of a prepotent response	Time to complete the task	20 min self-paced jogging and/or walking on a treadmill	Immediately	Young adults, fitness level not reported
Joyce et al. (2009)[122]	Stop-Signal Task	Inhibition of a prepotent response	SSRT	26 min pedaling on a cycle ergometer at 40% MAP	Immediately and 30 min	Young adults, 43 mL/kg/min for male and 37 for female
Yanagisawa et al. (2010)[123]	Stroop Task	Inhibition of a prepotent response	Interference cost	10 min pedaling on a cycle ergometer at 50%VO_{2peak}	15 min	Young adults, fitness level not reported
Chang et al. (2011)[124]	Tower of London Task	Planning	Total correct score and total move score	Two sets 10 repetitions at 40% and 70% 10-RM for nine muscles	Immediately	Young old adults, 889.94 METs/week
Chang et al. (2012)[125]	Tower of London Task	Planning	Total move score	20 min, two sets of 10 repetitions at 70% 10-RM for seven muscles	3 min	Young old Adults, 857 METs/week
Hyodo et al. (2012)[126]	Stroop Task	Inhibition of a prepotent response	Interference cost	10 min pedaling on a cycle ergometer at VT	15 min	Older adults, fitness level not reported
Alves et al. (2012)[127]	Stroop Task	Inhibition of a prepotent response	Time to complete the task	30 min walking at 50%–60% HR or two sets of 15 maximal repetitions for six muscles	Immediately	Young old adults, fitness level not reported
Hung et al.	Tower of	Planning	Total move score	20 min pedaling on a	Immediately,	Two groups of

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(2013)[128]	London Task			cycle ergometer at 60%-70% HRR	30 min and 60 min	young adults, 1205.00 METs/week for control group and 1134.50 for exercise group
Tam (2013)[129]	Stroop Task	Inhibition of a prepotent response	Time to complete the task and error rate	15–30 min stairs climbing at 50%–70% of HR_{max}	Immediately	Young adults, fitness level not reported
Byun et al. (2014)[130]	Stroop Task	Inhibition of a prepotent response	Interference cost	10 min pedaling on a cycle ergometer at 30% of VO_{2peak}	5 min	Young adults, fitness level not reported
Chang, et al. (2014)[131]	Stroop Task	Inhibition of a prepotent response	Incongruent RT	20 min pedaling on a cycle ergometer at 65% VO_{2max}	5 min	Three groups of young adults, 35.25, 45.52, and 56.21 mL/min/kg

Abbreviations: HR_{max} = maximal heart rate; HRR = heart rate reserve; MAP = maximum aerobic power; MWC = maximal work capacity; RT = reaction time; SSRT = stop-signal reaction time; VT = ventilator threshold.

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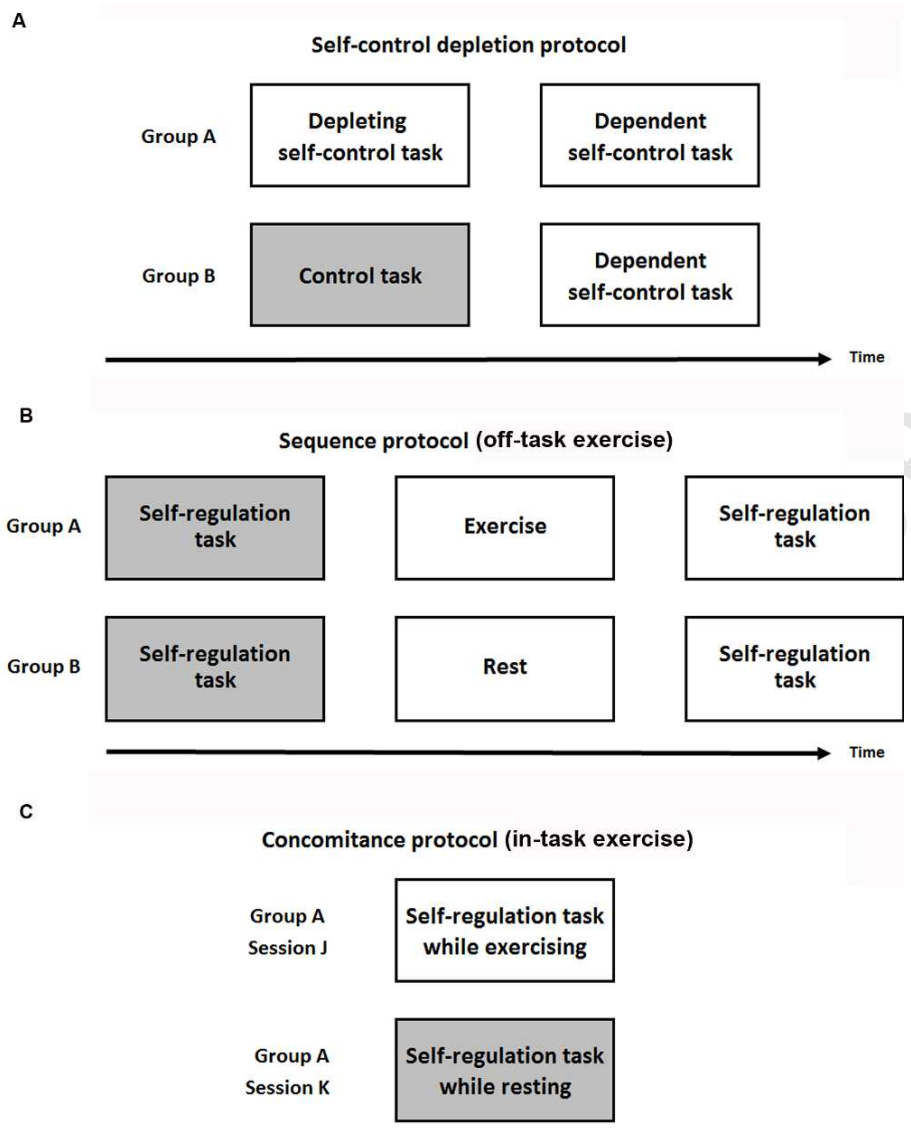

Fig. 1 Time course of three protocols used in exercise psychology to study the effect of acute exercise on self-regulation and executive functions. For the three panels, a grey box indicates baseline or the reference condition. In panel B, two designs can be used for sequence protocols, a between-subjects design (two groups of participants, one for each condition) as shown in the figure or a within-subjects design (the same group performing two different sessions, one session for each condition).

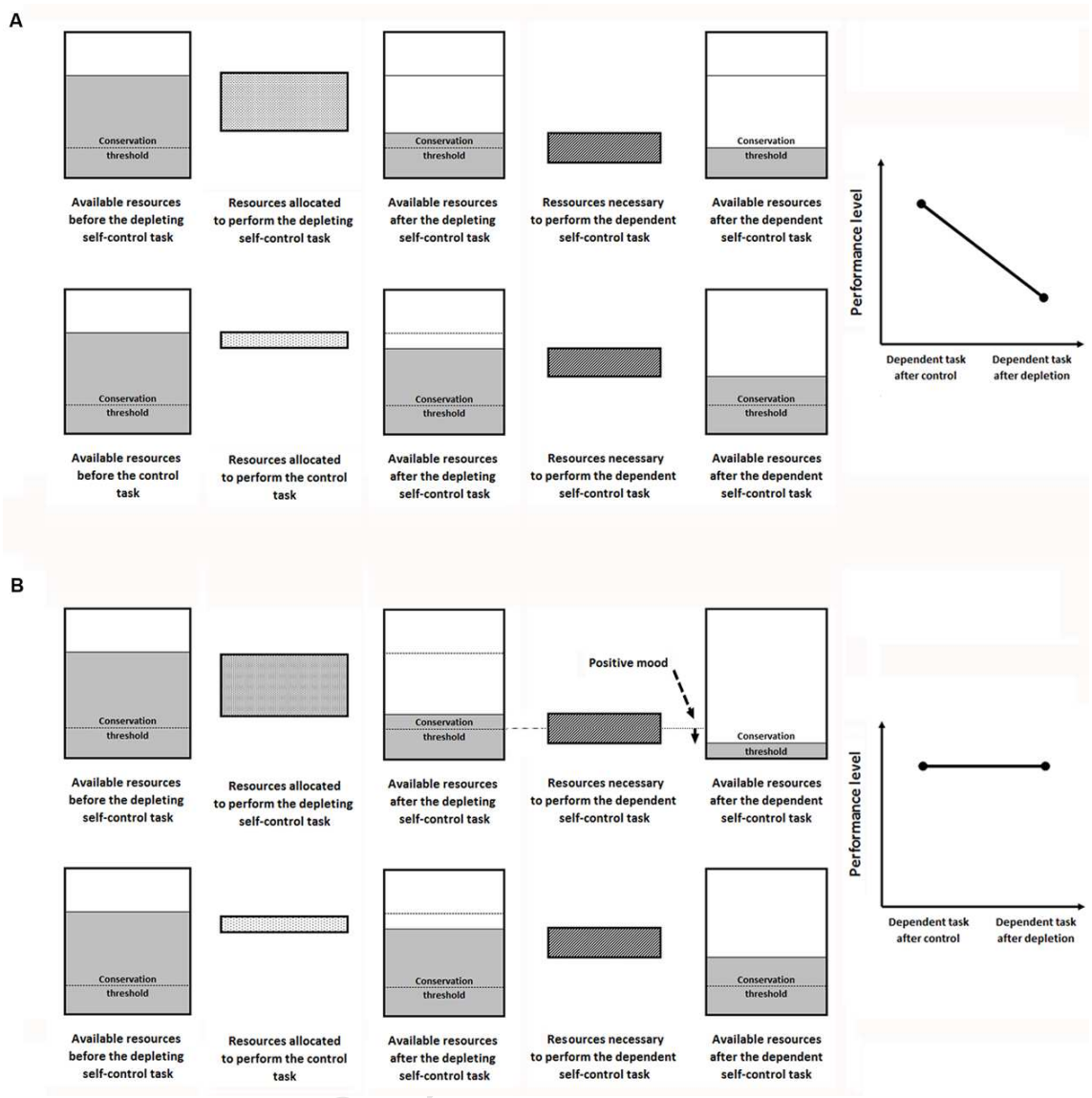

Fig. 2 Detrimental effect of self-control depletion (A) and facilitating effect of positive mood (B) on performance level of dependent self-regulation task according to Baumeister's strength model of self-control.

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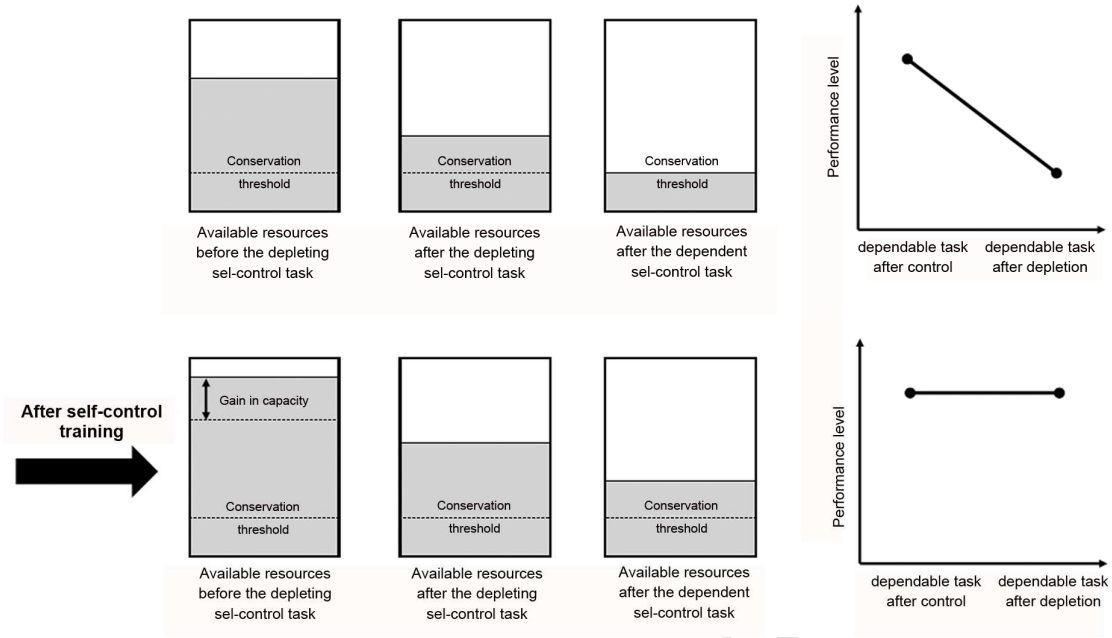

Fig. 3 Illustration of the capacity hypothesis explaining a lower detrimental effect of self-control depletion after self-control training.

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