Review

Executive functions and self-regulation

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Self-regulation is a core aspect of adaptive human behavior that has been studied, largely in parallel, through the lenses of social and personality psychology as well as cognitive psychology. Here, we argue for more communication between these disciplines and highlight recent research that speaks to their connection. We outline how basic facets of executive functioning (working memory operations, behavioral inhibition, and task-switching) may subserve successful self-regulation. We also argue that temporary reductions in executive functions underlie many of the situational risk factors identified in the social psychological research on self-regulation and review recent evidence that the training of executive functions holds significant potential for improving poor self-regulation in problem populations.

A fruitful collaboration

For a long time, the literature on executive functions (EFs) from cognitive psychology and the social and personality psychological literature on self-regulation have largely led separate lives [1]. This is regrettable, as both fields may benefit greatly from each other's insights and expertise. Recent years, however, have seen significant attempts to link the two areas. This new rapprochement is being brought about by the integration of concepts such as working memory capacity (WMC) [2,3] and response inhibition [4] into social psychological and personality models of self-regulation. In this article, we review several major lines of research that have already profited from forging such a connection.

Self-regulation and self-control

The study of successful self-regulation and its failure has a long history [5,6]. Self-regulation can be broadly defined as goal-directed behavior, typically within at least a minimum temporal perspective. Common examples include achievement-related behaviors, personal strivings, and the regulation of shared goals in close relationships. In contrast, the term 'self-control' is commonly used to demarcate a narrower subset of self-regulatory processes: those that aim to override unwanted, prepotent impulses or urges (such as the urge to indulge in a high-calorie desert when on a diet).

Broadly speaking, successful self-regulation entails three main components [5,7]: (i) standards of thought, feeling, or behavior that individuals endorse, mentally represent, and monitor; (ii) sufficient motivation to invest effort into reducing discrepancies between standards and actual states; and (iii) sufficient capacity to achieve this (i.e. reduce the discrepancy) in light of obstacles and temptations along the way. People may fail at self-regulation owing to a lack of standards or monitoring thereof, a lack of motivation, or a lack of capacity – in that logical order, because even abundant capacity would be of little use without a direction and the motivation to use it. This article is primarily concerned with how EFs subserve the capacity aspect of self-regulation, although we will on occasion consider representational and motivational aspects as well.

Executive functions

According to an influential taxonomy [8], there are three basic EFs: working memory operations such as the maintenance and updating of relevant information ('updating'), inhibition of prepotent impulses ('inhibition'), and mental set shifting ('shifting'). Updating is closely connected with the construct of working memory [1,9] and refers to the ability to keep information in an active, quickly retrievable state and shield this information from distraction [2]. Inhibition refers to the ability to 'deliberately inhibit dominant, automatic, or prepotent responses when necessary' ([8], p. 57). Shifting, also referred to as task-switching, refers to the ability to shift back and forth between multiple tasks or mental sets [10]. In this article, we limit the discussion to these three major elementary functions, although more fine-grained analyses of subcomponents [11,12] and more extensive lists of functions exist [13].

Different experimental tasks serve as indicators of the three basic EFs [8,13]. Operation span (see Box 1) and *n*-back measures, for instance, have been found to reflect primarily the updating function (working memory), consistent with the high task demands of maintaining and updating task-relevant information [8]. Inhibition is typically assessed with versions of the Stroop [14] or stop-signal task [4] in which participants have to inhibit or override a prepotent response. Task switching is operationalized with paradigms that allow inferring the time it takes subjects to mentally switch between two or more simple task sets (i.e., switch costs [10]). More complex tasks such as the Wisconsin Card Sorting Test tap into a combination of EFs [8,13].

Forging the link between EFs and self-regulation

In the following sections, we highlight several ways in which EFs and self-regulation may be intricately linked and provide a necessarily selective (due to space constraints) review of recent research that has supported

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Box 1. Measuring working memory capacity

The past few decades have seen considerable advances in the development and validation of WMC measures. One widely used method is operation span (OSPAN) performance (see [98] for a review]. In OSPAN-tasks, participants have to engage in a primary processing task (e.g., memorizing presented information). At the same time, they have to engage in an interfering secondary processing task (e.g., indicating via a keypress whether a presented equation is true or false). Participants performing an OSPAN task see items such as: IS 3 + 6 = 8? (keypress) 'CHAIR'. After three to eight items are presented in a sequence, the participant is asked to recall the words in their serial order. Thus, participants have to update the information relevant to the primary task (i.e., the words) and shield this task-relevant information from interfering information imposed by the secondary task. The number of trial items correctly recalled, weighted by trial length, serves as a measure of WMC. Individual differences measured with OSPAN tasks have been shown to predict performance on a wide range of real-world cognitive abilities such as language comprehension, reading comprehension, reasoning abilities, and lecture note-taking [31]. Research in social and personality psychology has now observed links between OSPAN performance and success at emotion regulation, mental control, impulse control, dealing with stressful situations, and regulating personal and relationship goals (see main text).

these connections. Our review is based on four broad propositions. First, we argue that the three broad facets of EFs (updating, inhibiting, and shifting) support important mechanisms in an individual's self-regulatory goal pursuits (see Table 1 for an overview). Second, EFs such as working memory, traditionally viewed as a 'cool' cognitive concept, may be implicated in the regulation of 'hot' processes such as unwanted emotional experiences, desires, and cravings. Third, we propose that temporary reductions in EFs may be a common mechanism at the heart of several situational risk factors contributing to self-regulation failure. Fourth, because EFs are trainable, at least to some extent, such improvements may translate to better behavioral self-regulation. Recent research has taken a number of methodological approaches to demonstrate these connections (see Table 2). Of particular importance for the present purpose is evidence that EF measures developed in cognitive psychology contribute to self-regulatory outcomes in theoretically meaningful ways (i.e., as predictor, as process moderator, and as process mediator).

Table 1. Connections between executive functions and self-regulatory mechanisms

Executive functions	Self-regulatory mechanisms
Working memory operations	• Active representation of self-regulatory goals and standards • Top-down control of attention toward goal-relevant information and away from attention-grabbing stimuli • Shielding of goals and standards from interference • Suppression of ruminative thoughts • (Down-)regulation of unwanted affect, desires, and cravings
Behavioral inhibition	• Active inhibition of prepotent impulses and habitual, 'mindless' behaviors
Task-switching	• Flexible switching between different means subserving the same (self-regulatory) goal ('means-shifting') • Switching between multiple goals ('goal-shifting/balancing')

Working memory operations and self-regulation

Active representation. As outlined above, successful self-regulation entails the representation of goals and goal-relevant information [2,15]. Working memory may directly subserve the active mental representation of an individual's self-regulatory goals (recruited from long-term memory) and the associated means by which these goals can be attained [15,16]. Without an active representation of such goal-related information, self-regulation is directionless and bound to fail [5] unless individuals have fully habitualized, automatic self-regulatory routines at their disposal [17,18].

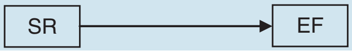
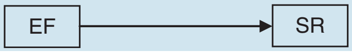
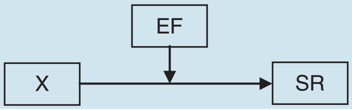
Executive attention. Attention can be regarded as one of the main 'battlefields' of self-regulation, as stimulus-driven influences and goal-directed processing often compete for limited attentional resources [19]. According to the elaborated intrusion theory of desire [20], for instance, tempting stimuli may automatically attract attention due to their motivational salience. To the degree that individuals fail to redirect attention away from the tempting stimulus, desire-related thoughts and emotions may receive additional elaboration in working memory and develop into 'elaborated desires' [20]. Elaborated desires use up WMC [21] and thus may crowd out of working memory other goal representations.

Cognitive research has shown that WMC plays a primary role in how well people are able to resist the attention-grabbing power of visual distractors in various cognitive tasks [2,22]. Recent work has applied this idea directly to the domain of self-regulation (sexual interest, alcohol) using viewing time and eye-tracking paradigms [23,24]. These studies suggest that WMC supports proactive forms of self-regulation by enabling individuals to resist the attentional capture of tempting stimuli at early stages of processing.

Goal shielding. In a related vein, directing and redirecting executive attention to goal-relevant information may be the primary mechanism by which self-regulatory goals are 'shielded' from competing goals or other distractions [25]. According to this view, goal shielding is the consequence of sustained attention to a goal or task [26] and provides an indirect or 'passive' form of inhibitory control (see Box 2). The ensuing mental state in which individuals 'zoom in' on the goals they want to achieve may closely correspond to what has been called an implementation or action-orientation mindset in self-regulation research [27,28].

One important observable consequence of effective goal shielding is that individuals should display stronger correspondence between their goal standards and their behavior when working memory resources are plentiful [29–33]. Conversely, limited or low working memory should lead to a stronger correspondence between automatic or impulsive processing and behavior because individuals may follow less effortful courses of action in the absence of a well-functioning goal shielding mechanism [29]. Numerous studies support these predictions [23,34–38]. For instance, when faced with the opportunity to consume tempting sweets, low WMC individuals act more strongly in line with their automatic affective reactions toward the food, whereas high WMC individuals act more strongly in line with the goal to forego sweets [23].

Table 2. Different approaches to the study of executive functions and self-regulation

Conceptual approach	Example research questions
EF[a] as outcome 	• Does dealing with strong cravings consume working memory resources?
EF as predictor 	• Does WMC predict mind-wandering in daily life? • Which executive function is most strongly related to emotion regulation?
EF as outcome and predictor 	• Do separate executive functions have negative aftereffects on each other?
EF as process moderator 	• Are impulsive precursors better predictors of risky sexual behavior among people low in inhibitory control?
EF as process mediator 	• Are the effects of stereotype threat on performance brought about by temporary reductions in working memory capacity? • Does repeated training boost inhibitory control and does this training gain in turn translate into improved self-control in everyday life?

[a] EF, measure of an executive function; SR, self-regulatory activity (independent variable) or self-regulatory outcome (dependent variable); X, predictor variable, situational manipulation, or intervention. Note that EF as outcome and predictor is a special approach that has been inspired by research on self-regulatory resource depletion (see text). The EF as process moderator approach can yield insights into the extent to which the effectiveness of self-regulatory processes depends on available executive functions. The EF as process mediator approach has the potential to reveal how (temporary or long-term) changes in EF may underlie changes in self-regulatory outcomes.

Suppression of ruminative thoughts. The capacity to focus attention on goal-relevant information should also relate to people's ability to regulate their own thoughts. Accordingly, several studies have shown a negative relationship between WMC and the extent of thought intrusions in standard thought suppression tasks [39,40]. This effect may be driven by a superior capacity of high WMC individuals to direct their attention to alternative mental contents thus leading to passive inhibition of the contents that need to be suppressed. In further support of the critical role of WMC in thought control, an intriguing experience sampling study showed that high WMC was related to less mind-wandering during challenging activities in daily life [41].

Box 2. Active vs. passive inhibition

Recent cognitive and neurocognitive research has argued for a distinction between two forms of inhibition: direct ('active') inhibition and indirect ('passive') inhibition through competition [99]. Active inhibition refers to the idea that certain regions in the prefrontal cortex (PFC) such as the inferior frontal gyrus are specialized for inhibitory top-down control. Such active inhibition may be implemented via selective inhibition of prepotent responses via basal ganglia networks that communicate closely with the PFC [100] or via more global inhibitory PFC projections [99]. This type of inhibition is 'active' in the sense that the PFC targets certain goal-inconsistent responses (e.g., the impulse to grab a cookie from a shared plate when on a diet) and pushes their neural activation below a critical threshold. This type of inhibition is characterized by a 'Do not do X' frame and is presumably captured by the inhibition factor identified in latent-factor analyses of executive functioning [8].

Passive inhibition, by contrast, refers to the idea that inhibition of mental contents may be the indirect consequence of activation of goal-relevant processing. Thus, sustained attention to a given goal or task set leads to a selective excitation of goal-relevant information that confers on this information an activity advantage over competing (goal-irrelevant or goal-incongruent) information. As a consequence of lateral inhibition [99], these alternative representations receive lower relative levels of activation so that goal-relevant contents are effectively shielded from interference. Passive inhibition through focused attention is similar to the way a spotlight illuminates an actor onstage while keeping the remaining scene in relative darkness. It can be described as a 'Do Y' frame and is presumably captured by how working memory capacity resources can be used to implement and maintain a specific goal or task-set focus in the PFC.

One implication of the distinction between active and passive inhibition for self-regulation research is that both forms of inhibition may independently contribute to impulse control and may be differentially impacted by situational risk-factors. Consistent with the former assumption, recent work shows that performance on a working memory capacity task and on a behavioral inhibition task each explained unique variance in people's ability to prevent their automatic affective reactions from influencing their eating behavior [38].

Down-regulation of unwanted affect and cravings. Despite its reputation as a genuinely 'cold' cognitive concept, working memory may also provide a mental 'workspace' for the regulation of emotion [42]. In fact, recent work has shown that WMC supports multiple stages of emotion regulation [43], including cognitive reappraisal and the regulation of emotional experience according to standards [44–46], such as the suppression of anger upon provocation [23].

Recent research has thus firmly established that working memory contributes to the successful self-regulation of behavior, including eating behavior, emotional responding, and aggression. This is in addition to the abundant evidence for working memory contributions to cognitive performance and other intellectual challenges.

Active inhibition of prepotent responses

A hallmark of successful self-regulation is the ability to actively inhibit or override behavioral responses such as (bad) habits and impulses that are incompatible with one's goals (see Box 2). Habits and impulses activate motor schemas that, unless inhibited, may be expressed in behavior once a certain threshold of activation is reached [30,47]. Using implicit reaction time measures [48] as marker variables for individuals' impulsive predispositions, a number of studies across diverse domains has demonstrated that individuals low in behavioral inhibition are more strongly influenced by these impulsive precursors than those high in inhibition [38,49,50]. Even long-term weight gain over the period of one year could be predicted in this manner from the interaction of impulsive food preferences and response inhibition measured at baseline [51]. Poor response inhibition has been implicated in a large number of further impulse-control problems ranging from drug (ab)use [52] and inadequate social responding [53] to sexual infidelity in romantic relationships [54].

Task-switching: shifting means versus shifting goals

In contrast to working memory operations and inhibition, surprisingly little work has addressed possible connections between task-switching and self-regulation. This section is intended to further stimulate possible links. Our starting point is the notion of the cognitive control 'dilemma' [55], which holds that self-regulating organisms have to solve trade-offs between the rigid pursuit of a focal goal or task-set ('rigidity') and the possibility of being open to alternative courses of action ('flexibility'). Whereas working memory and inhibition mechanisms can be seen as supporting rigid self-regulatory goal pursuit (by preventing external and internal distractions), the flexibility captured by task-switching may be related to self-regulation in two different ways.

On the one hand, high task-switching ability may facilitate goal pursuit by allowing individuals to abandon sub-optimal means (e.g., obstructed, costly, or otherwise low-utility means) and pursue alternative means to reach the same goal ('means-shifting'). For instance, people exhibit reduced switch costs in shifting from a current means to an alternative means when the overarching goal rather than the current means is made motivationally salient [56].

On the other hand, task-switching ability may also allow people to disengage from a self-regulatory goal and pursue tempting alternatives ('goal-shifting'). For instance, positive mood resulting from perceived goal progress may induce people to coast on that goal [57–59]. Often, such temporary disengagement from a self-regulatory goal may be part of a larger 'master plan' which individuals may use to optimally juggle the many different long- and short-term motivations and goals in life. The dieters who occasionally allow themselves to indulge without remorse in a tasty desert is a good example of such adaptive balancing of self-regulatory goals and short-term gratifications [58]. The line between adaptive balancing and self-regulatory failure appears to be a fine one, however, as a low threshold of disengagement from a focal self-regulatory goal can easily lead to rapid, repeated, and regretful overindulgence [5,60]. Whether task-switching is ultimately beneficial or maladaptive for one's self-regulatory agenda in a given context is a complex issue that appears to depend on the interplay of domain-related, motivational, and socio-cultural factors. Much more research is therefore needed on the interplay between task-switching and self-regulation.

Temporary reductions in EFs as a common mechanism underlying situational risk factors

Self-regulation can be temporally impaired by a large range of situational factors such as cognitive load [35,61,62], ego depletion [63–65], environmental or social stressors [66,67], alcohol intoxication [68], stereotype threat and other high-stakes situations [69,70], mortality salience [71,72], and interracial interaction [73]. These situational factors seem highly diverse at the surface. We argue, however, that most of the demonstrated impairments can be explained via state reductions in EFs as the underlying conceptual mechanism.

A temporary reduction in EFs can come about either as a result of the effects of concurrent task load [74] or it can be the consequence of prior high intensity engagement of EFs, a mechanism pioneered in the research program on 'ego depletion' by Baumeister and colleagues [64]. In support of this mechanism, many of the situational risk factors mentioned above have been shown to temporarily reduce EFs [75–77], although studies showing that state reductions in EFs mediate situational effects on actual self-regulatory behavior are still rare [77,78].

Regarding these negative aftereffects, Baumeister and colleagues convincingly argued that any act of self-control may deplete resources and negatively affect subsequent acts of self-control. Consistent with the finding that EFs share some common variance [8] and substantial overlap in subserving brain regions [79,80], different facets of EFs have been found to exert negative aftereffects on each other [81]. Recent findings, however, suggest that the magnitude of these aftereffects may be moderated by the ratio of common to specific task affordances [82].

Furthermore, evidence suggests that, on a physiological level, a temporary reduction in blood glucose may underlie ego depletion aftereffects [83,84]. In support of this suggestion, supplying participants with fast-acting glucose drinks appears to buffer against the depletion effect [83,84]. A completely separate line of research has shown that consuming glucose can boost performance on WMC and inhibition tasks within relatively short time frames [85–88]. Integrating these two lines of work would suggest, once again, that temporary reductions in EFs may constitute the most proximal psychological mediator of the observed glucose effects.

Boosting self-control by training EFs

In recent years, there has been significant interest in whether EFs can be improved via repeated training in clinical, risk, and healthy populations [89,90]. Although there is no doubt that EFs such as WMC can be improved through training [91] or related interventions such as mindfulness meditation [92], the extent to which these improvements generalize and show positive transfer on everyday behavior is strongly debated [93,94]. New findings suggest, however, that WMC training may in fact help to curb impulsive drinking in hazardous drinkers [95] and that behavioral inhibition methods can help to reduce problematic eating behavior [96,97]. Such transfer effects are typically found to be strongest among those who are both low on these EFs and harbor strong maladaptive impulsive tendencies that need to be overcome. These findings represent some of the most exciting evidence yet for a highly consequential role of EFs in self-regulation.

Concluding remarks

In the past few years, there has been increasing communication between cognitive and social and personality research on how people manage the pursuit of important long-term goals in the face of tempting alternatives. As we

Box 3. Questions for future research

- How exactly do the 'hot' systems of emotion and motivation interface with the 'cold' control systems of working memory? For instance, does the working memory system need some form of hedonic detector as suggested by Baddeley [1]?
- How can temporary reductions in executive functions best be prevented? Next to the role of glucose, which activities (e.g., meditation, rest, music, venting) lead to the fastest rates of recovery and which are counterproductive? Which structural or task-related features determine the extent of negative transfer effects?
- One of the most challenging and exciting routes for future research involves linking data from multiple levels of analysis, including (but not limited to) everyday behavior, (social-) cognitive, and neuropsychological measures (see [52] for an excellent example on smoking behavior). In such an integrative framework, can concepts from cognitive psychology perhaps serve as the central conceptual interface that connects the other levels of analysis?
- We suggested that switching may be either beneficial or detrimental for focal goal pursuit, depending on whether switching occurs at the level of means (i.e., overcoming obstacles) or at the level of goals (i.e., pursuing alternative goals). What factors determine the threshold above which people disengage and switch to alternative goals? Can existing measures of task-switching be modified to capture the ease with which persons switch, for instance, from pursuing long-term self-regulatory goals to pursuing short-term self-indulgent goals?
- On a more practical note, how can the collaboration between cognitive psychology, social psychology and neuroscience be further optimized?

hope to have shown, social and personality research on self-regulation has benefitted enormously from the application of concepts and experimental paradigms from cognitive control research. Similarly, cognitive research may be inspired by the diverse ways in which social and personality research have approached issues such as the study of situational and dispositional risk factors, multiple goal conflicts, and affect regulation, with the research program on depletion aftereffects being an excellent example for such an exchange [64,81]. Several open questions remain (see Box 3) and it is our hope that this integrative review will further stimulate conversation between subdisciplines interested in self-regulation, one of the most remarkable, yet fragile, strengths of human nature.

Acknowledgements

We thank Rachel Fisher, Hiroki Kotabe, Maike Luhmann, and Hans Marien for valuable comments.

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