

# Self-Determination, Self-Regulation, and the Brain: Autonomy Improves Performance by Enhancing Neuroaffective Responsiveness to Self-Regulation Failure

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The importance of autonomous motivation in improving self-regulation has been a focal topic of motivation research for almost 3 decades. Despite this extensive research, however, there has not yet been a mechanistic account of *how* autonomous motivation works to boost self-regulatory functioning. To address this issue, we examined the role of autonomy in 2 basic self-regulation tasks while recording a neural signal of self-regulation failure (i.e., the error-related negativity; ERN). Based on the notion that autonomy improves self-regulation, we anticipated that autonomous motivation would enhance neuroaffective responsiveness to self-regulatory failure and thus improve performance relative to controlled motivation. In Study 1 ( $N = 43$ ), we found that trait autonomy was positively associated with self-regulatory performance and that this effect was mediated by increased brain-based sensitivity to self-regulation failure, as demonstrated by a larger ERN. Study 2 ( $N = 55$ ) replicated and extended this pattern using an experimental manipulation of autonomy; when autonomous motivation was contextually supported, task performance increased relative to those for whom autonomy was undermined and those in a neutral condition. In addition, this effect was mediated by both increased perceptions of autonomy and larger ERN amplitudes. These findings offer deeper insight into the links among motivational orientation, brain-based performance monitoring, and self-regulation.

*Keywords:* autonomy, motivation, self-regulation, error-related negativity, performance monitoring

Human autonomy plays a pivotal role in self-regulation and performance. Whatever the behavioral domain, feelings of engagement, diligence, and vitality are higher when the motivation underlying a goal or behavior is autonomous or self-endorsed rather than pressured or controlled. As a result, goal-related performance tends to be better. Researchers attribute the effect of autonomy on goal-regulation to the fact that autonomy represents volition and cohesion in action. In other words, feelings of choice, interest, deep personal relevance, and internal causality underlie the experience of autonomous behavior, which energizes and sustains goal-striving.

This explanation, however, does not address the precise mechanism responsible for the self-regulatory or goal-related benefits of autonomy. Although many studies in social, personality, and motivational psychology have noted that autonomy is critical to good self-regulation, little is known about why, exactly, autonomy leads to better self-regulation. Therefore, we seek a deeper understand-

ing of the effect of autonomy on self-regulatory performance. By inspecting the neural mechanisms that link autonomy to self-regulatory performance, we hope to illustrate *why* autonomous motivation is more effective and efficient than other forms of motivation. More specifically, we assess error-related brain activity in order to test whether autonomy improves performance by promoting receptivity to instances when self-regulation should be improved.

## Self-Regulation and Self-Determination Theory

The ability to control and restrain automatic impulses and habits in the service of goal attainment is the oft-cited crux of self-regulation (cf. self-control; Barkley, 1997; Miyake et al., 2000), but it also refers more generally to the many processes individuals use to manage behavior, thoughts, and emotions (Fujita, 2011). It is, therefore, an extremely important executive function and, indeed, one of the defining features of human behavior (Baumeister, Heatherton, & Tice, 1994; Damasio, 1994). Moreover, the failure of self-regulation is one of the central problems of the human condition. For instance, deficits in self-regulation are found in a large number of psychological disorders including attention-deficit/hyperactivity disorder [ADHD], antisocial personality disorder, borderline personality disorder, addiction, eating disorders, and impulse control disorders (Barkley, 1997; Pierce & Cheney, 2004). In contrast, good self-regulators—those who can aptly manage the circumstances and impulses that obstruct goal attainment—are happier, healthier, and more productive (e.g., Tangney, Baumeister, & Boone, 2004).

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Given the importance of self-regulation to adjustment and performance, it becomes important to understand the ways in which it can be enhanced. As it turns out, cultivating the right kind of motivation can help increase self-regulatory capacity and success. For example, if an individual is attempting to regulate his or her diet or trying to quit smoking, the reasons she or he draws upon to substantiate his or her self-regulatory effort can influence whether goal-regulation is successful or not (Muraven, Gagné, & Rosman, 2008). Indeed, 3 decades of research in self-determination theory (SDT) indicate that when motivation underlying regulatory efforts is autonomous and self-driven, rather than externally controlled, goal achievement is more likely (Deci & Ryan, 1985b, 2002, 2008).

### The Role of Autonomy in Self-Regulatory Performance

Self-determination theory suggests that autonomous motivation is an effective means to self-regulation because it is initiated and guided by choices that cohere with one's needs, values, and self-selected aspirations. Similarly, autonomously functioning individuals seek out choices and self-direction, feeling generally free of interpersonal coercion. For instance, an autonomously motivated high school student might complete his or her homework every night after school because she or he finds the work to be enjoyable and interesting (i.e., intrinsic motivation) or because she or he believes it is an important aspect of learning (i.e., personally endorsed value). In order to encourage autonomy, autonomy-supportive environments offer choice, enhance interest, and support inner motivational resources. In contrast, individuals with a controlled motivational orientation look to external prompts and controls to determine their behavior and experience their environment as restrictive. Accordingly, controlling environments use pressure, threat, and contingent regard to extract prescribed thinking and behavior, which undermines autonomy and promotes controlled motivation. To continue with the academic example, a controlled student might complete his or her homework because his or her parents require him or her to do so, or solely for the purpose of obtaining a desired grade.

Of central relevance to the current study is the finding that autonomy improves self-regulatory performance. Thus, because autonomous motivation is self-concordant, reflecting what a person truly desires, values, or finds interesting, it is associated with better self-regulatory success, compared to controlled forms of motivation. In the academic domain, for instance, autonomously motivated students study harder, pay more attention in class, ask more questions, and get better grades (Guay, Ratelle, & Chanel, 2008; Reeve, Bolt, & Cai, 1999; Sheldon & Elliot, 1998; Vallerand, Fortier, & Guay, 1997; Vansteenkiste, Simons, Lens, Sheldon, & Deci, 2004). They also show enhanced cognitive flexibility, conceptual understanding, and active information processing (Grolnick & Ryan, 1987). In the health regulation domain, autonomous motivation leads to superior self-regulation in weight loss and weight loss maintenance (Teixeira et al., 2010; Williams, Grow, Freedman, Ryan, & Deci, 1996), as well as in smoking cessation (Williams et al., 2006; Williams, Niemiec, Patrick, Ryan, & Deci, 2009), alcohol abstinence (Ryan, Plant, & O'Malley, 1995), and diabetes management (Williams, Patrick, et al., 2009). In the domain of environmental behavior, autonomous motivation

toward the environment has been shown to predict greater success in the achievement of personal environmental goals over the course of a 7-day assessment period (Osbaldiston & Sheldon, 2003). Autonomy also appears to play an important role in long-term persistence in sports (Pelletier, Fortier, Vallerand, & Brière, 2001), as well as persistence and problem solving on cognitive tasks (Moller, Deci, & Ryan, 2006).

Additional work suggests that when the social context supports autonomy by offering choices and promoting interest, autonomous motivation increases, and cognitive control is thus enhanced, including improved thought suppression and delay of gratification (Muraven et al., 2008), as well as increased concentration (Bernier, Carlson, & Whipple, 2010; Muraven et al., 2008) and superior inhibition of implicit biases (Legault, Green-Demers, Grant, & Chung, 2007; Legault, Gutsell, & Inzlicht, 2011). These studies are important in demonstrating that autonomous motivation (and the support thereof) is likely to boost both cognitive and behavioral performance.

Despite the abundance of work indicating that autonomy improves self-regulation and goal-related performance, a basic and mechanistic understanding of this effect is currently absent. That is, we do not really understand why autonomy improves performance on tasks and behaviors requiring self-regulation. Until now, the "mechanisms" used to explain the relative effectiveness of autonomous regulation over controlled regulation suggest that autonomy fosters relatively more energy (Muraven et al., 2008; Ryan & Deci, 2008) and automaticity (Legault, Green-Demers, & Eadie, 2009) during self-regulatory pursuits. However, these explanations do not delineate a clear process through which autonomy exerts its benefits. That is, they do not provide an explanation of *how* autonomy affects the processing of information and the monitoring and correcting of behavior in the service of optimal performance. Like previous motivation researchers, we propose that autonomy fosters superior behavioral performance through better cognitive control. However, we go a step further by proposing a mechanism for this effect. Specifically, we suggest that autonomy bolsters self-regulation by amplifying brain-based sensitivity to self-regulation failure.

### Autonomy and Performance: The Mediating Role of Error Sensitivity

Because autonomy facilitates goal directed behavior and protects against self-regulatory depletion (Moller et al., 2006; Muraven, 2008; see Inzlicht & Schmeichel, *in press*), it follows that it might also promote more adaptive responses to self-regulatory errors and failures—responses that might in fact enhance further performance and goal pursuit. Autonomy promotes behavioral persistence in a wide variety of contexts that require continuous self-regulation over extended periods of time (e.g., studying, dieting, exercising, quitting smoking, etc.). This constant self-regulatory effort and attention makes failure (and its accompanying distress) unavoidable. Considering the high probability of self-regulatory failures, errors, and setbacks in any domain requiring cognitive, affective, and behavioral control, it becomes clear that adaptive responding and behavioral adjustment following such failures is important in minimizing further errors and in predicting the success of future performance (Rabbitt & Rodgers, 1977). Successful self-regulation, in other words, requires that people

notice, orient, and react to errors when they occur, so that they can learn from them and thus minimize future instances of them (Holroyd & Coles, 2002). Therefore, we propose that autonomy enhances self-regulatory performance because it encourages receptivity to self-regulation failures.

Why should autonomy promote such responsiveness to errors? Two fundamental components of autonomous functioning are the acceptance of negative affect (Reeve, 2009) and nondefensiveness to threatening self-relevant information (Hodgins & Knee, 2002; Hodgins et al., 2010). As such, we theorize that errors, failures, and negative feedback should be attended to in a receptive and responsive manner when the motivation underlying behavior is autonomous. Indeed, past research has shown that when people are autonomously motivated, they are less defensive and ego-protective and tend to openly acknowledge negative affect, criticism, and personal shortcomings (Hodgins & Liebeskind, 2003; Weinstein et al., 2011). Controlled motivation, on the other hand, is associated with increased defensiveness and denial in response to threatening self-relevant information (Hodgins et al., 2010). In line with these findings, we suggest that autonomy increases vigilance in performance monitoring by promoting awareness of error-related distress. Because personal errors are not affect-neutral events (quite the contrary, they alert us that goal attainment is in jeopardy) and because autonomy promotes deep and mindful engagement in action, it follows that feelings of autonomy should increase attention and emotional reactivity to those moments when self-regulation efforts have failed. This “caring about” one’s mistakes is a key adaptation to the environment that allows people to slow down, recalibrate their behavior, and ultimately improve their performance. Here, we examine whether autonomy enhances performance by augmenting reactivity to self-regulation failures at the level of the brain.

### The ERN: A Distress Signal of Self-Regulation Failure

Self-regulation involves a cognitive and affective system that is supported by specific brain areas and that facilitates optimal performance through its ability to plan, think flexibly and abstractly, acquire rules, attend selectively, initiate appropriate behavior, and inhibit inappropriate behavior. Based on cybernetic feedback-loop theories of self-regulation (e.g., Wiener, 1948), psychological and neuroscientific models of self-regulation suggest that two complementary systems are necessary to perform these various functions. In social and personality psychology, for instance, Carver and Scheier (1981) have described a “test” process that continually compares current behavior with ideal criteria, which then signals the “operating” process to elicit change toward a desired end. Similarly, Wegner (1994) has discussed the dual-action of a monitoring process, which scans for lapses in self-control, and an operating process, which acts to rectify any self-control failure. Although both monitoring and operating systems are important, the monitoring system is especially critical because it determines when self-control needs to be initiated. One of the best known neural correlates of self-control in general, and the monitoring system in particular, is the error-related negativity (ERN; Falkenstein, Hohnsbein, & Hoormann, 1991; Gehring, Goss, Coles, & Meyer, 1993).

The ERN is an event related potential (ERP) that is characterized by a pronounced negative deflection on electroencephalogra-

phy (EEG) that occurs within 100 ms of making an error on a task and is thought to be generated by the anterior cingulate cortex (ACC; Dehaene, Posner, & Tucker, 1994). Holroyd and Coles (2002) have suggested that the ERN reflects an error detection system that monitors performance and detects incongruity between intended and actual responses (see also Yeung, Botvinick, & Cohen, 2004). This process is implemented in the ACC (Kerns et al., 2004)—a brain structure that connects to both limbic and prefrontal regions of the brain and is attuned to response conflict, negative affect, errors, uncertainty, and psychological pain (Bush, Luu, & Poser, 2000; Ridderinkhof, Ulsperger, Crone, & Nieuwenhuis, 2004; Shackman et al., 2011).

Another view of the ERN suggests that, rather than simply reflecting attention to errors or discrepancies between desired and actual responses, the ERN is in fact linked to motivational and affective responses to such errors (Bartholow, Henry, Lust, Saults, & Wood, 2012; Hajcak & Foti, 2008; Hajcak, McDonald, & Simons, 2003; Inzlicht & Al-Khindi, 2012; Luu, Collins, & Tucker, 2000). Indeed, it has been suggested that the ERN might partially reflect a “distress signal” when performance is worse than expected (Bartholow et al., 2005, p. 41). This perspective asserts that ERN magnitude is associated with the value placed on errors and that increased motivation will amplify the ERN (Weinberg, Riesel, & Hajcak, 2012). Extending this recent motivational view, we suggest that the quality—and not just the quantity—of motivation matters when it comes to enhancing the ERN. That is, autonomous motivation is expected to be related to the degree to which performance is monitored and improved. Because feelings of autonomy promote acknowledgment of negative affect (rather than denial or suppression), as well as the integration of mistakes and personal faults (e.g., Weinstein et al., 2011), autonomous motivation should predict sensitivity to errors in performance. To the extent that the ERN reflects such an affective response to errors, autonomous motivation should enhance the ERN.

### The Role of Autonomy in the ERN

Although some recent research has examined patterns of brain activation associated with autonomous and controlled motivation in general (see Murayama, Matsumoto, Izuma, & Matsumoto, 2010; as well as Lee & Reeve, 2012), knowledge of the brain-mediated mechanisms through which autonomy influences self-regulation processes is limited. Only two correlational studies (in the domains of prejudice regulation and education) have implied a link between autonomous motivation and the ERN. Specifically, it has been suggested that those who display more personal reasons for inhibiting prejudice demonstrate increased ERN amplitude when failing to suppress bias relative to those with more external reasons (Amodio, Devine, & Harmon-Jones, 2008). Additionally, intrinsic academic motivation among 3rd to 5th graders has been correlated with larger ERNs (Fisher, Marshall, & Nanayakkara, 2009). Although these studies suggest that autonomy is related to increased neural responding to self-regulation errors, the link between general autonomy and brain-mediated self-regulation is unknown. More importantly, we are not aware of any studies that have examined how experimental changes in autonomy might impact the brain bases of self-regulation on performance tasks. Therefore, to fill this gap and provide a more complete picture of the link between autonomy and performance, we assess how

brain-implemented performance monitoring relates to trait differences in autonomy as well as how it may be affected by experimental manipulations of autonomy. By increasing our understanding of the neurophysiological processes that mediate autonomy's impact on self-regulation, we can join recent work (i.e., Lee & Reeve, 2012; Murayama et al., 2010) in shedding much-needed light on the neural bases of self-determination and offer additional validation of the real, far-reaching difference between autonomous and controlled motivation.

## Overview of Studies

Our goal was to understand how autonomous motivation enhances performance-based self-regulation. To do so, we assessed performance monitoring in the anterior cingulate cortex during two tasks requiring self-regulation. In Study 1, we examined associations among trait autonomy, self-regulatory performance, and neuroaffective responses to self-regulation failure (i.e., the ERN). In Study 2, we assessed the impact of state manipulations of autonomy on self-regulation and the ERN. We expected that both trait autonomy and state-induced autonomy would increase performance on the self-regulation task (i.e., by reducing the number of performance errors) and that this effect would be mediated by the heightened neuroaffective responding to those errors, that is, larger ERNs.

## Study 1

### Method

**Participants and procedure.** In exchange for course credit, 43 participants (28 women) from the University of Toronto Scarborough were invited to complete a computer task while brain activity was recorded. Participants' age ranged from 18 to 30 ( $M = 19.3$  years;  $SD = 1.97$ ). Before electrophysiological recording, participants were asked to complete a trait measure of motivational orientation.

#### Measures.

**Trait motivational orientation.** Individual differences in motivational orientation were assessed using the General Causality Orientation Scale (GCOS; Deci & Ryan, 1985a). The GCOS consists of 12 vignettes describing interpersonal scenarios, followed by a list of responses that represent either an autonomous (12 items), controlled (12 items), or impersonal/helpless orientation (i.e., an absence of motivation; 12 items). These dimensions are thought to represent relatively enduring aspects of personality. Items reflecting an autonomous orientation illustrate a preference for interest-enhancing and optimally challenging situations and a tendency to interpret social contexts as autonomy-supportive rather than controlling or imposing. In contrast, the controlled orientation assesses the extent to which a person is oriented toward being controlled by rewards, deadlines, structures, ego-involvements, and the directives of others. The impersonal orientation taps personal ineffectiveness and a general lack of motivation. Such individuals are likely to believe that attaining desired outcomes is beyond their control and that achievement is largely a matter of luck or fate. An example item from the GCOS asks respondents to rate on a 7-point scale "the most important consideration when embarking on a new career." The autonomous ori-

entation item states, "How interested I am in that kind of work"; the controlled orientation item states, "Whether there are good possibilities for advancement"; and the impersonal orientation item states, "Whether I could do the work without getting in over my head." Internal consistency was  $\alpha = .77$  for the autonomous motivation subscale;  $\alpha = .72$  for the controlled motivation subscale, and  $\alpha = .74$  for the impersonal (i.e., no motivation) subscale.

**The go/no-go task.** After completing the GCOS, participants performed the Go/No-Go task, which served as the main behavioral indicator of self-regulatory performance. Stimuli consisted of the letter *M* (the "Go" stimulus) and the letter *W* (the "No-Go" stimulus). Participants were required to press a button when the "Go" stimulus appeared and to refrain from pressing the same button when the "No-Go" stimulus appeared. Each trial consisted of a fixation cross ("+") presented for 500 ms, followed by either a "Go" or "No-Go" stimulus for 100 ms. The maximum time allowed for a response was 500 ms, and the intertrial interval was 50 ms. Participants first completed a practice block and then completed six experimental blocks, each consisting of 40 "Go" trials and 20 "No-Go" trials (presented randomly). The performance score was based on errors of commission (going on a No-Go trial) rather than the incongruity effect because there is no latency-based response for correct No-Go trials (that is, the correct response is no response), and thus it is not possible to generate incongruity effects for the Go/No-Go task.<sup>1</sup> Moreover, we stressed accuracy rather than speed by encouraging participants to respond as accurately as possible. It should also be noted that this task indeed required self-control. That is, because "Go" was the dominant trial type, "going" (i.e., pushing the button) became the dominant response. Thus, "No-Go" trials required self-regulation since participants had to suppress or inhibit their prepotent response to press the "Go" button.

Finally, a primary behavioral indicator of posterror adjustment, namely, posterror slowing (PES), was calculated. PES refers to the prolonged reaction time (RT) on trials following an error compared to RTs following correct trials (Rabbitt, 1966) and is thought to reflect the recruitment of executive control resources in the service of correcting performance. PES was computed as the difference in reaction time for correct responses following correct trials versus correct responses following incorrect trials.

**Neurophysiological recording.** Continuous EEG during the Go/No-Go task was recorded using a stretch Lycra cap embedded with 32 tin electrodes (Electro-Cap International, Eaton, Ohio). Recordings were digitized at 512 Hz using Advanced Source Analysis (ASA) acquisition software (Advanced Neuro Technology B.V., Enschede, the Netherlands) with average-ear reference

<sup>1</sup> No-go errors (i.e., "going" when instructed not to) were used as the basis for both ERN and performance analyses, rather than go errors (i.e., "not going" when instructed to "go"), as it is not possible or appropriate to generate an ERN for go errors. Go errors are errors of omission and thus they do not produce a button-press response. As we have discussed, ERNs must be locked to a response. For this same reason, ERP response negativity in response to correct trials (see Figure 1) was also locked to correct go trials rather than correct no-go trials. For the sake of completeness, however, we include associations between motivation and go errors here. Autonomy was negatively associated with making go errors,  $r(42) = -.38$ ,  $p < .01$ , whereas neither controlled nor impersonal orientations were associated with go errors.

and forehead ground. EEG was corrected for vertical electrooculogram artifacts (Gratton, Coles, & Donchin, 1983) and digitally filtered offline between 0.1 and 15 Hz (fast Fourier transform implemented, zero phase-shift Butterworth filter). Epochs were defined as 200 ms prior to and 800 ms subsequent to response. The EEG signal was baseline-corrected by subtracting the average voltage during the 200 ms time period prior to the response. Artifacts were automatically detected with  $-75 \mu\text{V}$  and  $+75 \mu\text{V}$  thresholds. Data for these epochs were averaged within participants independently for correct and incorrect trials and then grand-averaged within the respective conditions. The ERN was defined as the minimum peak deflection occurring between 50 ms pre-response and 150 ms postresponse at the frontocentral midline electrode (FCz). ERNs were based on no fewer than six artifact-free error trials (Olvet & Hajcak, 2009b).

## Results and Discussion

We hypothesized that trait autonomy would be positively related to both task performance (i.e., self-regulatory effectiveness) and brain-based error monitoring. Thus, as autonomous motivation increased, we anticipated that ERN amplitude would increase and errors would decrease. In addition, we anticipated that error monitoring would mediate the association between autonomy and performance. Finally, we expected that neither controlled nor impersonal motivation would be associated with error monitoring or performance, thereby providing evidence that it is the quality—and not simply the quantity—of motivation that really matters.

**Autonomous motivation and self-regulation.** The pattern of correlations (see Table 1) suggested that as autonomous motivation increased, so did performance (as measured by number of errors of commission),  $r(42) = -.35, p < .05$ , and ERN amplitude,  $r(42) = -.38, p < .01$  (see Figure 1 for a scatterplot of autonomy and the ERN). In turn, the ERN was correlated with number of performance errors,  $r(42) = .34, p < .05$ . An examination of partial correlations ensured that, even after controlling for the possible effect of error rate, a significant association between autonomy and the ERN remained,  $r(42) = -.30, p < .05$ . Moreover, we assessed correlations between the correct related negativity (CRN; the neurophysiological response to making a correct response) and the remaining variables. Importantly, this pattern of results revealed that the CRN was unrelated to performance and not significantly related to autonomy. This finding

suggests that effects of the ERN, as a function of autonomy, are specifically related to error processing rather than performance monitoring, more generally. To further underscore this point, we assessed correlations between the ERN difference score (i.e., ERN–CRN) and related variables. This “difference wave” approach is important because it allows us to cancel out processes common to all performance monitoring and to specifically isolate our variable of interest, error processing (Luck, 2005). The pattern of associations for the ERN remained intact (see Table 1). Figure 2 illustrates ERN and CRN as a function of high and low trait autonomy.

Dipole source localization confirmed that the ERNs were generated in an area consistent with the ACC. That is, coordinates of the preauricular-nasion (in millimeters) were  $x = 0.1, y = 0.1, z = 60.0$ ; dipole strength was 65.48 nAm, and this source accounted for 84.1% of the variance of the signal.

We next examined the process via which autonomous motivational orientation predicted improvements in self-regulatory performance. The mediating effect of the ERN on the link between autonomy and performance was ascertained using the bootstrap method outlined by Preacher and Hayes (2004, 2008). Again, we used the ERN–CRN difference score in this analysis, to hone in on error processing (Luck, 2005). Results are presented in Figure 3. First, as noted above, an analysis of behavioral performance revealed that autonomy was negatively related to number of errors on the Go/No-Go,  $t(42) = -2.41, p < .05$ . Second, as autonomy increased, so did ERN difference scores,  $t(42) = -2.27, p < .05$ , with more autonomy associated with higher (more negative) ERN difference scores. Third, after controlling for autonomy, the ERN difference score significantly predicted task performance,  $t(42) = 2.34, p < .05$ . To ascertain the indirect effect, percentile-based bootstrap confidence intervals (CI) and bootstrap estimates of standard errors were generated based on 5,000 bootstrap samples. The indirect effect was reliable,  $M = -.18 (SE = .09)$ , 95% bootstrap CI =  $-.40$  to  $-.03$ , suggesting that the ERN mediates the link between autonomy and performance on the self-regulation task.

Inspection of behavioral posterror adaptations revealed that, although autonomy was weakly associated with posterror slowing ( $\beta = .18$ ), this link was not significant ( $p = .25$ ). Given that past research has failed to find group differences in posterror slowing on the Go/No-Go task (e.g., Inzlicht & Al-Khindi, 2012), this

Table 1  
Descriptive Statistics and Pearson Correlations for Main Variables in Study 1

	<i>M</i>	<i>SD</i>	Commission errors	Omission errors	ERN	CRN	ERN–CRN	PES
Autonomy (trait)	5.41	0.66	-.35*	-.38**	-.38**	-.12	-.35*	.18
Commission errors	14.47	10.61	—	.53**	.34*	.02	.43**	-.32*
Omission errors	3.64	4.51		—	.28†	-.12	.40**	-.06
ERN	-6.66	4.57			—	.50**	.87**	-.17
CRN	-3.36	2.28				—	-.07	-.20
ERN–CRN	-3.31	3.87					—	-.09
PES	63.74	50.41						—

Note. Theoretical range for trait autonomy is 1–7. The ERN, CRN, and ERN–CRN are scored negatively, as they represent negative-going waveforms; thus, more negative scores represent greater ERP amplitude. ERN = error-related negativity; CRN = correct related negativity; ERP = event-related potential; PES = posterror slowing.

†  $p < .10$ . \*  $p < .05$ . \*\*  $p < .01$ .

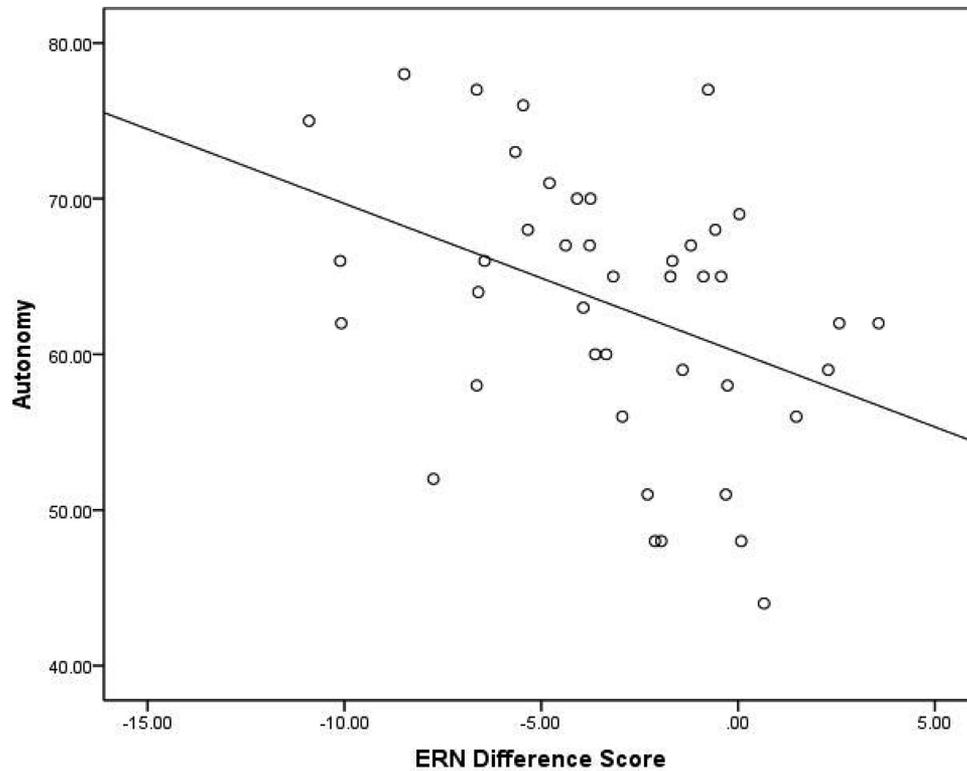


Figure 1. Scatterplot of autonomy and the ERN (Study 1). ERN = error-related negativity.

result is not entirely surprising (we revisit this issue in Study 2 using a different task and a direct induction of autonomy). See Table 1 for descriptive statistics for posterror slowing.

**Controlled motivation and self-regulation.** We also examined associations between controlled motivational orientation, on one hand, and performance and error monitoring, on the other. The assessment of this relationship is important because previous work has suggested that general motivational magnitude is associated with the ERN (e.g., Weinberg, et al., 2012). However, we propose that it is the quality—rather than simply the quantity—of motivation that boosts self-regulation by enhancing error detection. In support of our expectation, controlled motivation was not significantly associated with performance errors,  $r(42) = .12$  (*ns*), nor the ERN,  $r(42) = -.17$  (*ns*). Interestingly, although it did not quite reach significance, the association between impersonal orientation (i.e., those showing a lack of motivation) and the ERN showed the opposite pattern compared to the two types of motivation,  $r(42) = .23$ ,  $p = .16$ , suggesting that as motivation diminishes, the ERN does as well. Like controlled motivation, impersonal orientation was not significantly related to performance,  $r(42) = .10$  (*ns*).

In sum, these findings suggest that autonomous motivation is significantly related to error processing, which serves to increase self-regulation. In contrast, the association between controlled motivation and error processing was negligible, suggesting that controlled motivation is not a sufficient predictor of the ERN. Rather, the source of motivation (i.e., autonomous vs. controlled) is important in understanding the neural mechanism of self-regulation. These results lend support to the idea that the quality of motivation (and not just the quantity) is a significant factor in

signaling when self-regulation has failed (but not necessarily when it has succeeded!).

## Study 2

Study 2 sought to extend Study 1 in various ways. First, rather than measure trait autonomy, we used an experimental induction of autonomy to test the causal impact of autonomous motivation on self-regulatory performance. According to self-determination theory, autonomous motivation is multifaceted and can be enhanced in various ways. That is, the following situations are said to be autonomy-supportive: the provision of choice; the promotion of interest and intrinsic motivation, the support of inner motivational resources, the provision of optimal challenge, and the administration of informational feedback and structure. In contrast, controlling environments override autonomy and instead induce motivation by emphasizing external demands. In line with this reasoning, we either supported autonomy toward a task (i.e., by enhancing choice and interest, which are key means through which to target autonomy) or exerted external control over completion of the task.

Second, we used a different measure of self-regulatory capacity, the Stroop task, to verify the robustness of the effect. Indeed, it may be argued that the Go/No-Go and the Stroop assess different dimensions of self-regulation. That is, because the Go/No-Go requires the ability to keep changes in task instruction online (i.e., “No-Go” vs. “Go”), it taps into the switching component of self-regulation. The Stroop, on the other hand, is a canonical test of inhibitory control. Compared to the Go/No-Go, which establishes prepotent responding by presenting twice as many Go trials

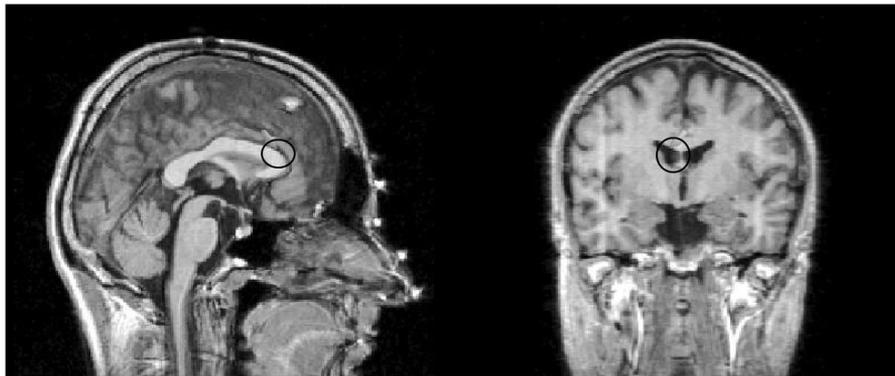
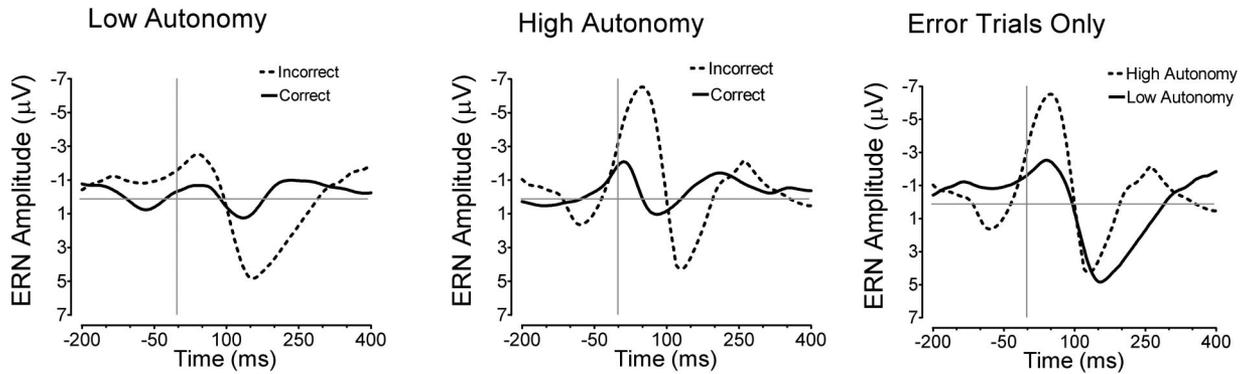


Figure 2. Differences in the ERN as a function of trait autonomy (median split). ERN = error-related negativity.

as No-Go trials (thus, “going” becomes the dominant response because it is more frequent), the Stroop entails a more deeply entrenched prepotent response tendency (i.e., reading) that may be more difficult to override. In other words, for the Go/No-Go, inhibitory control involves the stopping of a habitualized motor response. Conversely, the Stroop assesses inhibition of the prepotent response to read the visual presentation of words. Because reading is automatic and well-learned, the dominant response is to read the text presented rather than to respond to other physical characteristics of the text (e.g., naming the color of the ink with which the word is written). Thus, although both tasks represent self-regulatory ability, they are somewhat different in the degree to

which they assess inhibition and switching capacities. Finally, in addition to assessing the mediating effect of the ERN in the association between autonomy-support and performance, we also examined the intervening role of intrinsic task motivation and perceived task value—two key features of autonomous motivation.

## Method

**Participants and procedure.** Fifty-five undergraduates (29 male)<sup>2</sup> at the University of Toronto Scarborough participated for either course credit or \$15.00 compensation. Participants’ age ranged from 18 to 30 years ( $M = 19.6$  years;  $SD = 2.03$ ). Participants were invited to complete a study titled “Brain Games,” wherein they performed a computer task while EEG was recorded. In order to manipulate autonomous and controlled motivation, participants were randomly assigned to one of three conditions (i.e., autonomy-supportive, controlling, or neutral). Our experimental manipulation was based on the notion that the enhancement of choice and interest increases autonomous motivation, whereas the administration of pressure and requirement thwarts it (Deci & Ryan, 2000, 2008; Moller et al., 2006).

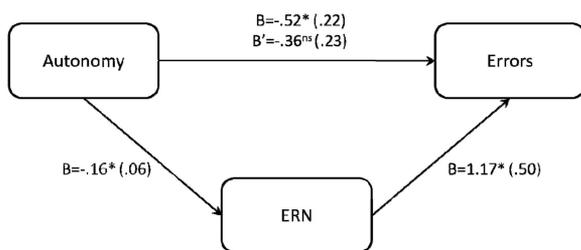


Figure 3. The mediating role of error monitoring in the link between autonomy and performance (Study 1). Unstandardized regression coefficients are presented. ERN is operationalized as the ERN–CRN difference score. ERN = error-related negativity; CRN = correct related negativity; ns = not significant. \*  $p < .05$ .

<sup>2</sup> One reason why slightly smaller sample sizes tend to have sufficient power to detect motivational and affective effects on the ERN (e.g., Amodio et al., 2008; Fisher et al., 2009; Gonsalkorale, Sherman, Allen, Klauer, & Amodio, 2011) is because the ERN is a highly reliable and stable measure (Olvet & Hajcak, 2009a, 2009b; Weinberg & Hajcak, 2011).

Participants in the two experimental conditions (i.e., the autonomy-supportive and controlling conditions) read a descriptive list of four computer tasks (i.e., “brain games”) These games included (a) The Mental Distraction Game; (b) A Game of Accuracy; (c) Ignore Your Impulses, and (d) Cognitive Response Latency Test. Unbeknownst to participants, each selection described the same task (i.e., the Stroop task) in a unique way. Participants in the autonomy-supportive condition ( $n = 18$ ) were instructed to select the game they most wanted to perform and were then directed toward the task (which was always the Stroop task). It is worth noting that we attempted to tap into choice (directly) and interest (indirectly) in the autonomy induction because both are key experiences in autonomous motivation. In the controlled condition, participants ( $n = 18$ ) saw the list of choices but were pressured by the experimenter (who was unaware of the nature and purpose of the study) to perform task *d* (i.e., the Cognitive Response Latency Test). In the neutral condition ( $n = 19$ ), participants went directly to the Stroop task, without being presented with a list of choices. After completion of the Stroop, various motivational variables were assessed.

### Measures.

**Stroop task.** The main behavioral measure was performance on a color-naming Stroop task (MacLeod, 1991). This task, which lasted about 20 min, consisted of color words (i.e., red, green, blue, and yellow), each of which was presented in a color that either matched (congruent) or did not match (incongruent) the written meaning of the word. Self-regulation is required on incongruent trials in order to correctly identify the color of the ink with which the word is printed and to inhibit prepotent responding to the semantic meaning of the word. Responses were measured by having participants press a corresponding color button on a response box. In each trial, a fixation cross (“+”) appeared for 500 ms, followed by the stimulus word presented for 200 ms. Participants were given 800 ms in which to respond. The task contained 10 blocks, each consisting of 32 congruent trials (i.e., the baseline response, e.g., the word “yellow” in yellow ink) and 16 incongruent trials (e.g., the word “yellow” in blue ink). An incongruency effect was calculated by subtracting reaction times on correct congruent trials from reaction times on correct incongruent trials. Performance was calculated by tallying the number of errors on incongruent trials (i.e., the self-regulation trials). We used incongruent errors as the main measure of performance to remain consistent with Study 1 and because we emphasized accuracy on the task, rather than speed. As in Study 1, posterror slowing was also calculated.

**Neurophysiological recording.** EEG during the Stroop task was recorded and processed according to the technique outlined in Study 1.

**Self-determined task motivation.** Self-determined motivation toward the Stroop task was measured using the Intrinsic Motivation Inventory (McAuley, Duncan, & Tammen, 1989; Ryan, 1982). That is, we measured three key constituents of autonomous motivation toward the Stroop task, including *perceived choice*, *task interest/enjoyment*, and *task value/usefulness*. Perceived choice assessed the extent to which participants felt as though they freely chose to do the task (four items; e.g., “I felt like it was my choice to do this task”;  $\alpha = .75$ ). The interest/enjoyment scale reflected intrinsic motivation toward the task (four items; e.g., “I enjoyed doing this computer task very much”;  $\alpha = .89$ ), and the

value/usefulness dimension tapped the extent to which the value of the task had been internalized, or had come to be seen as having some importance (four items; e.g., “I think that doing this activity is useful for improved concentration”;  $\alpha = .76$ ). Correlations among these three dimensions ranged from .53 to .75.

**General task motivation.** Apart from measuring self-determined motivation, we also assessed other dimensions of motivation toward the Stroop task, in order to verify that any experimental effects could be attributed specifically to changes in autonomous motivation rather than changes in motivation more generally. Moreover, we wanted to ensure that the controlling task instructions did not undermine participants’ motivation to complete the task. This check is important because, in order to test whether the ERN can be attributed to motivational quality rather than quantity, we need to verify that both autonomous and controlled motivational inductions increased motivation overall. Thus, although we expected that those in the autonomy-supportive condition would be more autonomously motivated, we nonetheless anticipated that both motivation groups would be *generally motivated to complete the task*. To ascertain dimensions of motivation that are relatively less proximal to autonomy than those tapped by the self-determined task motivation measure (above), we assessed *task confidence* (three items; e.g., “I feel like I would do well on this task in the future”), and *effort exerted* (two items; e.g., “I tried to do well on this task”).

## Results and Discussion

We hypothesized that motivational quality, rather than quantity, would predict the degree to which self-regulation failure would be detected and performance enhanced. Specifically, we anticipated that the support of autonomous motivation toward the task would produce better performance and a larger ERN relative to the controlling and neutral conditions. We also expected that the causal relationship between autonomy-support and performance would be reliably mediated by neural responsiveness to self-regulation errors.

**Correlations.** Correlations and descriptive statistics for each variable are presented in Table 2. As in Study 1, inspection of correlations provided preliminary support for our hypotheses. Autonomy (coded: autonomy-supportive = 1; neutral = 0; controlling = -1) was negatively related to performance errors,  $r(54) = -.38, p < .01$ , and associated with more negative ERN amplitudes,  $r(54) = -.43, p < .01$ . In turn, ERN amplitude (negatively scored) was associated with a reduction in performance errors,  $r(54) = .45, p < .01$ . Correlational analyses also revealed that the CRN was unrelated to autonomy and not significantly related to performance. Furthermore, autonomy and performance remained associated with the ERN–CRN difference score. These data describe a pattern of associations that is specific to error processing and not responses in general.

**Self-determined task motivation.** We wanted to verify that that autonomy-supported participants did indeed show increases in self-determined (i.e., autonomous) motivation. An analysis of the self-reported self-determination data supported the causal role of the autonomy manipulation in increasing perceived self-determination toward the task (i.e., feelings of choice, interest, and task value). That is, those in the autonomy-supportive condition experienced greater perceived task choice ( $M = 4.38; SD = 0.69$ )

Table 2  
Descriptive Statistics and Pearson Correlations for Main Variables in Study 2

	<i>M</i>	<i>SD</i>	Self-det.	Incongruent errors	Congruent errors	Incongruent effect	ERN	CRN	ERN–CRN	PES
Autonomy (condition)			.41**	–.39**	–.40**	–.04	–.43**	.02	–.36**	.36**
Self-determination	3.61	0.98	—	–.30*	–.30*	.18	–.46**	.00	–.38**	.25†
Incongruent errors	24.98	17.09		—	.73**	.00	.45**	.16	.30*	–.26†
Congruent errors	22.24	16.77			—	–.27*	.42**	–.08	.39**	–.31*
Incongruency effect	77.56	59.57				—	.02	.20	–.08	.00
ERN	–5.33	3.38					—	.08	.86**	–.48**
CRN	–1.03	2.08						—	–.58**	.16
ERN–CRN	–4.30	4.04							—	–.47**
PES	40.18	95.83								—

Note. Theoretical range for self-determination scores is 1–7. The ERN, CRN, and ERN–CRN are scored negatively, as they represent negative-going waveforms; thus, more negative scores represent greater ERP amplitude. Self-det. = self-determination; ERN = error-related negativity; CRN = correct related negativity; ERP = event-related potential; PES = posterror slowing.

†  $p < .10$ . \*  $p < .05$ . \*\*  $p < .01$ .

than those in the controlling ( $M = 3.62$ ;  $SD = 0.62$ ) and neutral ( $M = 3.91$ ;  $SD = 0.60$ ) conditions,  $F(2, 52) = 7.38$ ,  $p < .001$ ,  $\eta_p^2 = .21$ . Autonomy-supported participants also reported more interest in the task ( $M = 4.25$ ;  $SD = 1.54$ ), and placed greater value on the task ( $M = 4.95$ ;  $SD = 1.32$ ), compared to controlled ( $M_{\text{interest}} = 3.30$ ;  $SD = 1.35$ ;  $M_{\text{value}} = 3.57$ ;  $SD = 1.03$ ) and neutral participants ( $M_{\text{interest}} = 3.16$ ;  $SD = 0.96$ ;  $M_{\text{value}} = 3.84$ ;  $SD = 1.07$ ),  $F_{\text{interest}}(2, 52) = 4.23$ ,  $p < .05$ ,  $\eta_p^2 = .13$ ;  $F_{\text{value}}(2, 52) = 8.22$ ,  $p < .001$ ,  $\eta_p^2 = .22$ . These data indicate that the autonomy manipulation exerted its intended effect on various dimensions of perceived autonomy. There were no statistically meaningful differences in perceived self-determination among neutral and controlled participants—although controlled participants felt they had marginally less choice than those not shown the list of task choices (i.e., neutral participants),  $F(1, 35) = 2.63$ ,  $p = .11$ ,  $\eta_p^2 = .06$ .

**General task motivation.** We also wanted to confirm that, although the autonomy supported group displayed the greatest autonomous task motivation (as shown in the previous paragraph), both motivation groups experienced general motivation toward the task. This check was important to ensure that subsequent effects on the ERN could be attributable to the quality of motivation rather than the quantity. Thus, we analyzed additional dimensions of motivation to ensure that the controlling task instructions did not reduce participants' self-reported level of motivation toward the Stroop task. Supporting the notion that controlled participants showed a general desire to complete the task, results suggested that both controlled ( $M = 4.86$ ;  $SD = 1.52$ ) and autonomy-supported participants ( $M = 4.63$ ;  $SD = 1.34$ ) demonstrated greater confidence in their ability to complete the task than did neutral participants ( $M = 3.68$ ;  $SD = 1.34$ ),  $F(1, 35) = 6.85$ ,  $p < .05$ ,  $\eta_p^2 = .15$  (controlled vs. neutral);  $F(1, 35) = 4.76$ ,  $p < .05$ ,  $\eta_p^2 = .12$  (autonomous vs. neutral). Indeed, task confidence was similar for autonomy-supported and controlled participants ( $F < 1$ ). This suggests that our manipulation of autonomy and control increased general task motivation relative to the neutral group. A similar pattern emerged for effort exerted on the task, such that controlled ( $M = 4.89$ ;  $SD = 0.82$ ) and autonomy-supported ( $M = 4.87$ ;  $SD = 1.23$ ) participants exerted the same amount of effort on the task ( $F < 1$ ), which was greater than the effort reported by those in the neutral condition ( $M = 3.92$ ;  $SD = 0.85$ ),  $F(1, 35) = 13.67$ ,

$p < .001$ ,  $\eta_p^2 = .26$  (controlled vs. neutral);  $F(1, 35) = 7.57$ ,  $p < .01$ ,  $\eta_p^2 = .17$  (autonomous v. neutral). These results suggest that the motivational manipulation targeted autonomous motivation specifically and did not exert an undermining effect on general motivation toward the task for those in the controlled condition, as indexed by task confidence and effort.

**Performance.** Behavioral data were assessed using a one-way between-subjects analysis of variance (ANOVA). In line with our expectations, the experimental manipulation exerted an effect on the primary performance variable (i.e., incongruent errors, or Stroop errors),  $F(2, 52) = 4.36$ ,  $p < .05$ ,  $\eta_p^2 = .15$ . That is, those in the autonomy-supportive condition made fewer Stroop errors ( $M = 15.47$ ;  $SD = 10.67$ ) than those in the neutral condition ( $M = 27.16$ ;  $SD = 17.16$ ) and those in the controlled condition ( $M = 30.61$ ;  $SD = 18.42$ ). Planned contrasts suggested that the support of autonomy reduced Stroop errors relative to those in the neutral group,  $F(1, 35) = 7.63$ ,  $p < .01$ ,  $\eta_p^2 = .18$ . Autonomy-supported participants also committed substantially fewer Stroop errors than controlled participants,  $F(1, 34) = 6.45$ ,  $p < .05$ ,  $\eta_p^2 = .17$ . The neutral and controlled participants, however, showed no differences in Stroop errors ( $F < 1$ ). In addition, there were no meaningful group differences in the incongruency reaction time effect,  $F < 1$ .<sup>3</sup>

We also assessed performance effects for errors on congruent Stroop trials. We analyzed these separately because they are less central to self-control processes but also because the number of congruent and incongruent trials was not equal. Again, the motivational induction demonstrated an overall effect on congruent errors,  $F(2, 52) = 5.45$ ,  $p < .01$ ,  $\eta_p^2 = .16$ . Specifically, those whose autonomy was supported in the Stroop task made fewer congruent errors ( $M = 12.47$ ;  $SD = 9.16$ ) than those in the neutral ( $M = 19.75$ ;  $SD = 14.84$ ) and controlled conditions ( $M = 33.83$ ;

<sup>3</sup> This lack of effect is not entirely surprising. That is, the incongruency effect is an ambiguous indicator of performance because it may actually reflect greater deliberation during incongruent trials, which can sometimes be associated with better control rather than worse control. Because error rate is a clear indicator of performance, we were principally concerned with errors and not in the incongruency effect. Moreover, we instructed participants to be accurate rather than speedy, thus underscoring the need to focus on error effects.

$SD = 32.52$ ). Contrasts revealed that autonomy support reduced errors relative to both the neutral,  $F(1, 35) = 3.30, p = .08, \eta_p^2 = .09$  (marginal effect), and controlled conditions,  $F(1, 34) = 6.91, p < .05, \eta_p^2 = .17$ . In addition, controlled participants made marginally more errors than neutral participants,  $F(1, 35) = 2.78, p = .10, \eta_p^2 = .07$ .

In sum, these findings reveal that enhancing autonomy in relation to the task exerted a positive effect on task performance. In contrast, increasing external control showed no performance improvement on Stroop errors (as compared to doing nothing to influence task engagement) and actually hindered performance on congruent errors.

**Behavioral adjustment.** As in Study 1, we assessed behavioral adaptation following errors by calculating posterror slowing (PES) in reaction time (i.e., posterror RT minus postcorrect RT). Descriptive statistics and correlations with other variables can be found in Table 2. A one-way ANOVA with PES as the dependent variable revealed an overall effect of motivational condition on PES,  $F(2, 52) = 4.62, p < .01, \eta_p^2 = .14$ . Specifically, those whose autonomy was supported in the task showed greater PES ( $M = 91.08; SD = 136.09$ ) compared to those in the neutral condition ( $M = 24.89; SD = 35.21$ ),  $F(1, 35) = 4.21, p = .05, \eta_p^2 = .11$ , and compared to those who were motivated with controlling tactics ( $M = 7.95; SD = 71.23$ ),  $F(1, 34) = 6.02, p = .02, \eta_p^2 = .14$  (in fact, controlled participants showed nonsignificant posterror slowing). PES did not differ significantly between the neutral and controlled groups ( $F < 1$ ). These data indicate that the support of autonomy during the Stroop task caused participants to recalibrate

their behavior following errors relative to correct trials. This slowing effect underscores the notion that autonomy promotes processing of errors and response conflict, which promotes behavioral correction.

**The ERN.** A 3 (Condition: autonomy-supportive vs. neutral vs. controlling)  $\times$  2 (Response: error vs. correct) mixed-factor ANOVA with peak minimum amplitude as the dependent variable was performed. A significant main effect of response revealed that the waveform following error trials (i.e., the ERN) was significantly greater in magnitude ( $M = -5.33; SD = 3.93$ ) than the waveform following correct trials ( $M = -1.03; SD = 2.08$ ),  $F(1, 52) = 67.33, p < .001, \eta_p^2 = .56$ . In addition, there was a significant main effect of group,  $F(2, 52) = 5.14, p < .01, \eta_p^2 = .17$ , indicating that overall the waveform was smaller in the controlling ( $M = -2.54; SE = 0.41$ ) and neutral ( $M = -2.68; SE = 0.40$ ) conditions, relative to the autonomy-supportive condition ( $M = -4.22; SE = 0.41$ ). However, it is important to note that this main effect was qualified by a significant interaction between condition and response type,  $F(2, 52) = 4.09, p < .05, \eta_p^2 = .14$ . That is, although the three conditions showed similar amplitudes on correct trials (i.e., the CRN;  $F < 1$ ), the effect of condition on the ERN was significant,  $F(2, 52) = 7.71, p < .001, \eta_p^2 = .23$  (see Figure 4 for an illustration). To be specific, those in the autonomy-supportive condition displayed a larger ERN ( $M = -7.58; SD = 4.02$ ) than those in the neutral condition ( $M = -4.57; SD = 2.43$ ),  $F(1, 35) = 7.63, p < .01, \eta_p^2 = .18$ . Autonomy-supported participants also displayed a significantly larger ERN than those in the controlling condition ( $M = -3.88$ ;

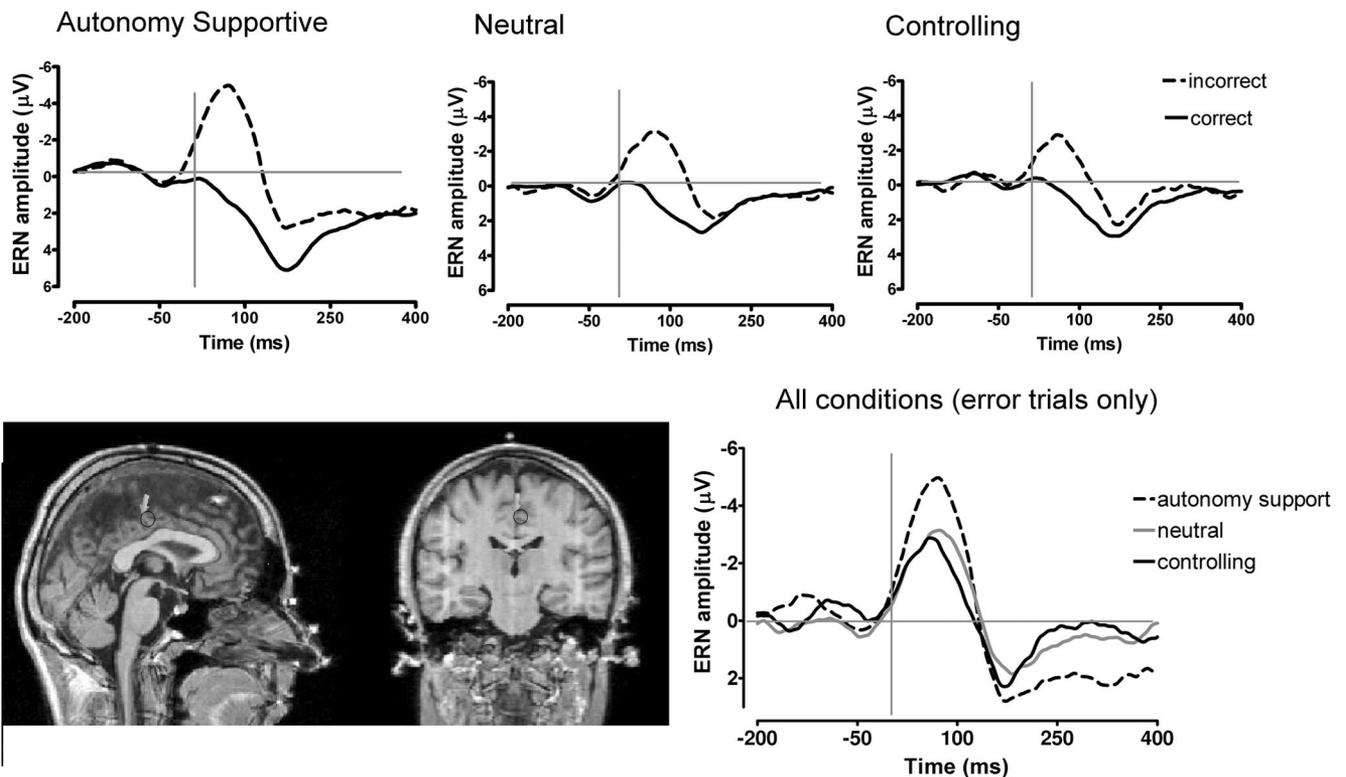


Figure 4. Differences in the ERN as a function of autonomy support. ERN = error-related negativity.

$SD = 2.24$ ),  $F(1, 34) = 11.59$ ,  $p < .01$ ,  $\eta_p^2 = .26$ . These results indicate that all three groups displayed comparable neural responses to successful regulation; it was instead their responses to self-regulation failure that differed. There was no significant ERN difference between the neutral and controlling conditions ( $F < 1$ ), which suggests that instilling pressure/control produces no more error monitoring than doing nothing to boost incentive. Finally, we verified that, although error rate was significantly associated with the ERN,  $F(1, 51) = 6.22$ ,  $p < .05$ ,  $\eta_p^2 = .11$ , condition remained a significant predictor of ERN amplitude even after controlling for error rate,  $F(2, 51) = 4.08$ ,  $p < .05$ ,  $\eta_p^2 = .14$ .

Dipole source localization confirmed that the ERNs were generated in an area around the ACC (preauricular-nasion coordinates, in millimeters, were  $x = .15$ ,  $y = 0.0$ ,  $z = 50.0$ ). Dipole strength was 66.33 nAm, and this source accounted for 91.8% of the variance of the signal. When using only 32 electrode channels, source localization in EEG is not as precise as certain other neuroscientific methods. Nonetheless, the localization found here is consistent with previous source localization (Pizzagalli, Peccoraro, Davidson, & Cohen, 2006) and magnetoencephalographic (Miltner et al., 2003) and intracerebral findings (Brázdil, Roman, Daniel, & Rektor, 2005).

In sum, these results suggest that motivation does indeed wield an influence on the ERN, but only when that motivation is autonomous. We can conclude that the presence of incentives or motivational salience in itself does not increase performance monitoring (as suggested by previous research; e.g., Weinberg et al., in press) but that effective task engagement is enhanced when motivation is experienced as volitional and self-driven.

**Autonomy and performance: The mediating roles of perceived self-determination and error monitoring.** Finally, we tested the mediating effect of both perceived self-determination and the ERN on the link between motivational condition and self-regulation performance (please see Figure 5). We chose a different mediation strategy from Study 1 because we wanted to examine two mediators rather than one; we also wanted to assess the link between the mediators. Therefore, a test of multiple mediation was performed using the SPSS modeling macro procedure, MEDTHREE, outlined by Hayes, Preacher, and Myers (2011). This multiple mediation procedure offered the advantage of testing two mediators simultaneously rather than separately, in order to determine the overall effect of both mediators, as well as

to obtain a clearer picture of the unique effects of each mediator. The total, direct, and indirect effects of condition on performance were estimated using a set of ordinary least squares regressions. To ascertain indirect effects, percentile-based bootstrap confidence intervals and bootstrap estimates of standard errors were generated based on 5,000 bootstrap samples.

A condition variable was calculated (autonomy-supportive = 1; neutral = 0; controlling = -1), which predicted perceived self-determination (i.e., the summation of choice, interest, and value),  $t(54) = 3.04$ ,  $p < .01$ , as well as ERN amplitude (i.e., after subtracting the CRN),  $t(54) = -2.52$ ,  $p < .05$ . Perceived self-determination also uniquely predicted ERN amplitude,  $t(54) = -2.46$ ,  $p < .05$ , and ERN amplitude, in turn, uniquely predicted performance,  $t(54) = 2.26$ ,  $p < .05$ . Using the bootstrap method, the total effect of all variables (i.e., condition, self-determination, and the ERN) on performance was significant (estimate = -4.02), with a 95% bootstrap confidence interval (CI) of -8.70 to -0.93 ( $SE = 1.98$ ). In addition, the unique indirect effect of the ERN on the link between condition and performance was significant, estimate = -2.61, 95% bootstrap CI = -6.10 to -.26 ( $SE = 1.50$ ). This suggests that the ERN mediates the link between condition and performance. Furthermore, although the unique indirect effect of self-determination on the path between condition and performance was not significant, it did exert a significant mediating effect on the link between condition and the ERN, estimate = -.95, 95% bootstrap CI = -2.62 to -0.042 ( $SE = .68$ ). Thus, the combined effect of both mediators on performance was reliable. These findings support our hypothesis and suggest that the manipulation of autonomy increases performance on the Stroop through heightened perceptions of autonomy and enhanced neural signals of self-regulation errors.

## General Discussion

This is the first article to illustrate a clear mechanism through which autonomous motivation increases self-regulatory performance. Using both personality and situational indicators of motivational orientation, we examined the role of autonomy in promoting performance on self-regulation tasks and, in addition, assessed the neural mechanism involved in this effect. Data from Study 1 suggest that trait-level autonomous motivational orientation is positively associated with self-regulatory performance. Study 2 lends causal support to Study 1 by establishing that the support of autonomous motivation (i.e., by enhancing choice and interest in the context of a self-regulation task) also increases self-regulatory performance. In both studies, the effect of autonomy on performance was significantly mediated by brain-based error monitoring. Moreover, in Study 2, the effect of autonomy-support on error monitoring was indirectly explained by increased perceptions of task choice, task interest, and task value, which are constituent features of autonomous motivation. Thus, when participants' autonomous task motivation was supported, ensuing feelings of autonomy and task importance were positively associated ERN magnitude, which was positively related to performance.

Complementing the finding that autonomous motivation promotes error-sensitivity at the neural level, Study 2 also demonstrated that autonomy-supported individuals displayed greater response slowing after errors, compared to neutral and controlled participants. In other words, whereas those in the controlled group

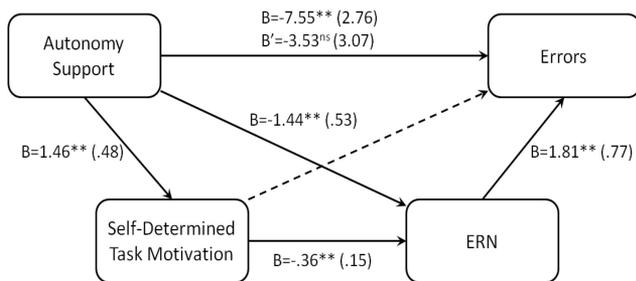


Figure 5. The mediating roles of self-determined task motivation and error monitoring in the link between autonomy support and performance (Study 2). Unstandardized path coefficients are presented. ERN is operationalized as the ERN-CRN difference score. ERN = error-related negativity; CRN = correct related negativity; ns = not significant. \*\*  $p < .01$ .

showed similar reaction times on trials immediately following their correct and incorrect responses, those in the autonomous motivation group took slightly longer after errors, suggesting increased error processing and correction (although their reaction times were not slower overall).

### The Quality of Motivation Is Key in Self-Regulatory Success

With this research, we wish to emphasize the importance of motivational quality in behavior and brain processes. All of the research on motivation and the ERN, for instance, has focused on the quantity of motivation, noting that the ERN increases along with the level of motivational engagement (for a review, see Weinberg et al., 2012). While motivational magnitude is certainly important in any self-regulatory activity, we suggest that the reasons underlying behavior are equally, if not more, important. That is, in the current work, autonomous motivation was related to the ERN, whereas controlled motivation was not (Study 1). Similarly, in Study 2, both autonomy-supported and controlled participants were motivated to complete the Stroop task (more so than the neutral group), but those who were autonomously motivated performed better and showed greater sensitivity to self-regulation error, at both neural and behavioral levels. Thus, we gave participants the option either to choose the task they most wanted to complete or to complete the task that we, the experimenters, wanted them to complete. Although it may seem that giving people the chance to choose the task they want (and are presumably most interested in) should elicit an increase in motivation, our data suggest that autonomy-supported participants were not necessarily more motivated toward the Stroop than controlled participants (pleasing the experimenter is indeed strong motivation) but rather more *autonomously* motivated. Accordingly, those who chose an interesting task displayed more intrinsic motivation and self-determination than did participants who completed the task at the experimenter's request. However, both motivation conditions demonstrated more confidence and more effort in the task compared to the neutral condition. In other words, both motivation groups exhibited a drive to complete the task, but they differed in the quality of this drive. Indeed, SDT suggests that engaging in that which is concordant with one's desires and goals is a more productive form of motivation. More external forms of motivation may appear to be equally as strong, at least on the surface or in the short term (e.g., the desire for wealth or fame), but to the extent that they are not autonomous, they are less likely to produce self-regulatory benefits or positive effects on well-being (Kasser, Kanner, Cohn, & Ryan, 2007; Kasser & Ryan, 1996; Ryan & Deci, 2000).

Thus, our findings offer a novel explanation for the self-regulatory benefits of autonomy. Whereas the mechanisms via which autonomy produces its deep behavioral engagement and success have previously been underresearched, we go beyond past research in self-determination theory by uncovering a basic neural mechanism underlying the effectiveness of autonomous self-regulation. In line with past work suggesting that the ERN is a primary signal for self-regulation *failure* (e.g., Inzlicht & Gutsell, 2007), we propose that the experience of autonomy heightens responsiveness to this signal. This finding may help to account for the effectiveness of autonomous self-regulation observed across

numerous behavioral domains, including food and exercise regulation, smoking cessation, medication management, and the regulation of academic and work behavior.

### Autonomy and Self-Regulation Failure: The Importance of Being Aware of Negative Affect and Threat

Despite the prominence of the cognitive interpretations of the ERN in particular and self-regulation in general, recent research suggests that the ERN is associated with affect—particularly negative affect (Inzlicht & Al-Khindi, 2012). Thus, in addition to reflecting conflict detection, the ERN (and perhaps, by extension, self-regulation) may represent an affective (Bartholow et al., 2012; Hajcak, MacDonald, & Simons, 2004) and defensive/motivational (e.g., Hajcak & Foti, 2008; Hajcak et al., 2003; Luu et al., 2000) response to that conflict (see Schmeichel & Inzlicht, *in press*). In other words, gaps in performance are met with negative affect and reactivity.

We suggest that, in order to better understand this recent view of the ERN, it may indeed be helpful to turn to the role played by autonomy. The link between autonomy and increased reactivity might, at first, seem counterintuitive. This is because, at a dispositional level, autonomous individuals tend to display more positive (rather than negative) affect, as well as less (rather than more) psychological defensiveness in comparison to controlled individuals. Specifically, autonomous individuals tend to perceive information, individuals, and experiences openly and accurately, without distortion (Hodgins, 2008; Hodgins & Knee, 2002), and having an autonomous motivational style is thought to predict flexibility and approach in relation to novel and challenging experiences, rather than denial or defensiveness (Lakey, Kernis, Heppner, & Lance, 2008). Nonetheless, it is important to consider the adaptive and dynamic role played by both negative affect and threat reactivity in signaling when performance goals have not been met. Indeed, these regulatory signals appear to be stronger when autonomy is high.

Thus, rather than suggesting a link with negative emotionality or trait-level defensiveness, our findings suggest that autonomously motivated behavior produces a stronger affective reaction when performance is not optimal—due to the high level of engagement and investment experienced. We therefore suggest that autonomy predicts better and more accurate *awareness and acceptance of negative affect and threat*, which results in improved spontaneous coping with such negative affect and threat, including dynamic adjustments to performance that can improve self-regulation (see Teper & Inzlicht, *in press*). Such adaptive strategies might include vigilance to threat and acknowledgment of negative affect. This improved self-regulation may help to explain why, in the long run, negative affect and psychological defensiveness are relatively low among autonomously motivated individuals.

Furthering the notion that autonomy may promote affective and motivational “tending” to errors, recent research suggests that autonomy, more than control, permits the acknowledgment of negative affect and personal faults (Weinstein et al., 2011), and increases openness to negative feedback (Hodgins & Liebeskind, 2003; Hodgins et al., 2010). Indeed, autonomous individuals are inclined to respond to failure in a mastery-oriented fashion by accepting responsibility and focusing on self-improvement (Koes-

ner & Zuckerman, 1994). Conversely, controlled individuals tend to deny or rationalize failure (Hodgins, 2008; Hodgins, Yacko, & Gottlieb, 2006; Lakey et al., 2008). Moreover, a criterion of autonomy-supportive contexts is that they acknowledge that errors—and their accompanying distress—are a natural part of the self-regulation/goal-seeking process and that, as such, they ought to be embraced for the information, accuracy, and authenticity that they provide (Reeve, 2009). It is possible, then, that autonomy should lead to preparedness and to attention to errors and other signals of self-regulation failure and that the ERN may underlie such awareness and openness to challenge and threat.

In sum, there are several reasons why autonomy might be negatively related to psychological defensiveness but positively related to “defensive” reactivity to threat and error. As a further point of clarification, there is some degree of semantic confusion between the term “defensive motivation” in ERN research (e.g., Hajcak & Foti, 2008; Weinberg et al., 2012) and the term “defensiveness” in the self-determination literature. The first is represented at a neuroaffective level within milliseconds of making a response, whereas the other is an overt behavioral manifestation of threatened self-esteem. More importantly, the ERN represents defensive motivation to the extent that it signifies a reactive, brain-level “gasp” at threat or error. This startle-based view of defensive responding is akin to preparedness or responsiveness to the situation at hand, which is qualitatively different from cognitive or psychological defensiveness—a process designed to protect self-esteem by ignoring and transforming the (often harsh) reality of a given situation. Indeed, our findings indicate that the interrelation among motivational orientation, negative affect, and threat awareness is more nuanced than previously suggested and that negative affect awareness and defensive reactivity (at the neural level rather than the behavioral level) may be adaptive responses germane to autonomy. Taken with other related findings (e.g., Legault, Al-Khindi, & Inzlicht, in press; Teper & Inzlicht, in press), the current research suggests that autonomy increases awareness of negative affect and threat, which serves the purpose of monitoring for discrepancies between actual and ideal behavior, and in doing so, prompts the increases in attention and perception, as well as the readiness for action, which is required for optimal self-regulation. This self-regulatory alertness helps to explain why autonomously motivated behavior is prone to succeed in meeting its regulatory objective. The continued investigation of the role of threat awareness and the resolution of negative affect in mediating the link between autonomy and various life outcomes—such as performance, decision making, goal and life satisfaction, and well-being—may prove to be a very fruitful avenue for future research.

### Boundaries of the Current Study

By mapping the neuroaffective process through which autonomous motivation bolsters performance on self-regulation tasks, this research joins recent efforts to understand the self-determined brain (see also Lee & Reeve, 2012; Murayama et al., 2010). It is important to note, however, that our findings may be limited to explaining how autonomous motivation affects performance on tasks where errors and self-regulation failures are likely. Undoubtedly, there are other key neurological mechanisms that mediate the effects of autonomous motivation more generally—mechanisms that extend beyond error monitoring and self-regulatory perfor-

mance. In particular, previous functional magnetic resonance imaging (fMRI) research has linked feelings of choice (a component of autonomy) to general increases in ACC activity (e.g., Walton, Devlin, & Rushworth, 2004). This finding coheres with our more specific event-related finding that autonomy activates the error responsiveness function of the ACC. More general brain differences in motivational orientation have also been noted. For instance, Lee and Reeve (2012) have recently suggested (again using fMRI) that feeling autonomously motivated, as opposed to feeling controlled, is related to increased activity in the anterior insular cortex—a brain region associated with feelings of agency. In addition, recent work has demonstrated that activity in the anterior striatum and prefrontal cortex is reduced when intrinsic motivation is undermined (Murayama et al., 2010). As we begin to understand the neurophysiology of human autonomy, it would be prudent for future research to consider how these broader patterns of (de)activation are related to more specific processes (as those described herein).

### Conclusion

Although previous work has indicated that autonomously motivated individuals show improved self-regulation relative to controlled individuals (e.g., Muraven, Gagné, & Rosman, 2007; Pelletier et al., 2001; Teixeira et al., 2010; Williams et al., 2009a, 2009b), we take this finding further by revealing (a) the causality of this effect and (b) its underlying neural implementation. Thus, whereas previous studies have attested that autonomy boosts self-regulatory ability, the precise cognitive and neuroaffective mechanisms remained relatively unexplored. Specifically, although past research has suggested that autonomy improves self-regulation by generating more “energy” and “vitality” available to the self (Moller et al., 2006; Muraven, 2008; Muraven et al., 2008), it is not precisely or mechanistically clear what energy and vitality mean or how they are represented. Past work on “process,” in other words, has relied on metaphors and less on actual information processing mechanisms. Here, we offer something more specific by demonstrating that autonomous motivation enhances basic self-regulation processes by increasing attention and emotional reactions to performance errors. Because controlled motivation does not elicit this neuroaffective effect, we suggest that the analysis of brain differences in the *quality* rather than the *quantity* of motivation is an important consideration. Indeed, cognitive models of self-regulation might be expanded by examining how autonomy further improves the error monitoring process.

In addition, by pointing to its neural underpinnings, we offer a contribution to self-determination research by clearly linking autonomy to the well-delineated performance monitoring function of the anterior cingulate cortex: autonomy increases error-related processing and distress in the service of enhancing self-regulation. Rather than reducing mind to brain function, the naturalization of autonomy instead lends additional evidence of the real, far-reaching difference between feeling autonomous and feeling controlled. Our findings underscore the importance of noncoercion in action and suggest that self-determination has a neural basis that plays a critical role in cognitive control and optimal performance.

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