EXPRESSIVE SUPPRESSION DELETERIOUSLY IMPACTS COGNITIVE ASPECTS OF MOTOR OUTPUT

by

Madison Niermeyer

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STATEMENT OF THESIS APPROVAL

The thesis of **Madison Niermeyer**

has been approved by the following supervisory committee members:

Yana Suchy, Chair **9/8/15**
Date Approved

Michael Himle, Member **9/8/15**
Date Approved

Matthew Euler, Member **9/8/15**
Date Approved

and by **Lisa Aspinwall**, Chair of

the Department of **Psychology**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

Growing evidence demonstrates that (a) executive functions (EF) become deleteriously affected by engagement in the emotion regulation strategy known as *expressive suppression* and (b) EF show considerable functional and neuroanatomical overlap with motor output. The current study aimed to bridge these two literatures by examining the relationships between naturally occurring expressive suppression and several different aspects of motor output, including action planning, action learning, and motor-control speed and accuracy. In addition we investigated whether any identified relationships could be explained by EF.

Fifty-one healthy young adults completed selected subtests from the Delis-Kaplan Executive Function System as indices of EF, a self-report measure of expressive suppression, and a computerized motor sequencing task (Push Turn Taptap task; PTT) designed to assess action planning, action learning, and motor-control speed and accuracy.

Hierarchical regressions using each aspect of PTT performance as the dependent variable revealed that higher-than-usual self-reported expressive suppression on the day of testing (relative to the two weeks preceding testing) was associated with longer action-planning latencies. This relationship was fully explained by EF. No other PTT variables related to expressive suppression on the day of testing.

These results suggest that increased expressive suppression in daily life

measurably degrades action planning, an aspect of motor output that is reliant on EF, highlighting the importance of factors that lead to intraindividual fluctuations in EF ability and motor performance.

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INTRODUCTION

The relationships among cognitive, affective, and motor processes as drivers of action or behavior have become increasingly apparent in recent years, leading to calls for conceptualizations that unify these three broad domains (Lewthwaite & Wulf, 2010). The present study draws upon two specific aspects of these relationships. First, there is a growing literature demonstrating functional and neuroanatomic overlap between certain aspects of motor output (e.g., action planning, action learning, and motor control) and executive functions (Koziol, 2014; Mirelman et al., 2012; Ridler et al., 2006; Rigoli, Piek, Kane, & Oosterlaan, 2012; Suchy & Kraybill, 2007; Suchy, Kraybill, & Larson, 2010). Second, there is a growing literature showing that engagement in the emotion regulation strategy known as *expressive suppression* has a deleterious impact on executive functions (Baumeister & Alquist, 2009; Franchow & Suchy, 2015; Hofmann, Schmeichel, & Baddeley, 2012; Schmeichel, 2007). Together, these findings suggest that expressive suppression might have a deleterious impact on motor output as well. However, these two literatures have been largely developing in parallel, and the impact of expressive suppression on motor output therefore remains relatively unexplored. The aim of the current study is to integrate these two literatures by investigating the impact of naturally occurring expressive suppression on executively demanding aspects of motor output.

Relationship Between Executive Functioning and Motor Output Processes

Executive functioning (EF) is a multifaceted neuropsychological construct that encompasses a variety of higher-order cognitive processes that allow an individual to engage in goal directed behavior (Cummings & Miller, 2007; Lezak, Howieson, Bigler, & Tranel, 2012; Stuss, 2011; Suchy, 2009). Numerous scholars have proposed that EF, which governs cognitive and behavioral control, is best thought of as an extension of the motor output system (Koziol, 2014). Ridler and colleagues (2006) argue that EF develops through the integration of additional prefrontal and cerebellar areas to a previously matured cortical cerebellar system that initially developed to facilitate coordinated movement. This idea is supported by evidence showing that motor coordination and EF abilities develop in tandem (Hartman, Houwen, Scherder, & Visscher, 2010; Rigoli et al., 2012) and that infant motor coordination predicts adult EF ability and relies on an overlapping set of neuroanatomical substrates in the prefrontal cortex, premotor area, and medial cerebellum (Ridler et al., 2006). Additionally, EF ability, but not other cognitive abilities, is associated with fall risk in neurologically healthy older adults (Herman, Mirelman, Giladi, Schweiger, & Hausdorff, 2010; Mirelman et al., 2012). Lastly, performance on motor sequencing tasks (e.g., Luria's [1966] "fist-edge-palm" task) is related to the integrity of the substrates that support EF (Lezak et al., 2012), as well as to performance on EF tests (Fama & Sullivan, 2002; Kraybill & Suchy, 2008; Suchy et al., 2010).

Despite their demonstrated association with EF abilities and the underlying EF substrates, motor sequence learning tasks are not widely used to assess EF. However, recent research using an electronic analogue to Luria's Fist-Edge-Palm task (i.e., the

"Push-Turn-Taptap" task; PTT) indicates that motor sequence learning tasks may offer numerous benefits over more commonly used measures of EF. For example, compared to traditional measures of EF, performance on the PTT task has been shown to be a better predictor of activities of daily living and declines in cognition and functional status over the course of a year among older adults (Kraybill & Suchy, 2011; Kraybill, Thorgusen, & Suchy, 2013; Suchy, Kraybill, & Franchow, 2011), and more sensitive to the subclinical consequences of mild traumatic brain injury (Suchy, Euler, & Eastvold, 2014). The promising clinical utility of the PTT task provides justification for further investigations that can help us refine our theoretical understanding of the relationship between EF and motor sequence learning. One way to approach this is to evaluate whether different aspects of motor sequence learning are affected by variables known to compromise EF performance, such as expressive suppression (ES).

Relationship Between Executive Functioning and Expressive Suppression

Expressive suppression (ES) refers to the intentional inhibition of facial and other behavioral expression of emotions, such as crying or laughter (Giuliani, Drabant, Bhatnagar, & Gross, 2011). The need to engage in ES is a common occurrence in daily life, and can be beneficial for a variety of prosocial behaviors when used in appropriate contexts (Gross, 2014). However, there are significant short-term costs associated with engaging in ES (Baumeister & Alquist, 2009; Inzlicht & Schmeichel, 2012). Experimentally manipulated ES has been shown to result in decreased performance on measures of EF, decreased physical stamina, impaired decision making capacity, and greater willingness to engage in shopping sprees, break diets, and reckless driving (Baumeister & Alquist, 2009; Bray, Martin Ginis, & Woodgate, 2011; Fischer, Kastenmüller, & Asal, 2012; Inzlicht & Gutsell, 2007; Muraven, Tice, & Baumeister, 1998).

Recent research has extended these findings from experimentally induced ES to naturally occurring ES in daily life. Franchow and Suchy (2015) developed a self-report measure that assesses the burden of ES in daily life. Using this measure, they demonstrated that individuals who had experienced higher than usual ES *on the day of testing* produced lower scores on the Delis-Kaplan Executive Function System battery (D-KEFS), comprised of a set of traditional EF tasks. This relationship held even after controlling for depression, processing speed, and working memory. Interestingly, the usual ES burden (i.e., over the course of two weeks preceding testing) was *un*related to EF; instead, it moderated the relationship between ES on the day of testing and EF, such that only those individuals who exhibited low ES burden over the course of the past two weeks were affected by high ES burden on the day of testing.

Relationship Between Motor Output and Expressive Suppression

Although the impact of ES on motor sequence learning has not been directly investigated, there is some indirect evidence that naturally occurring ES may negatively affect the motor output system. Specifically, invoking negative stereotypes, which appears to cause individuals to engage in ES in order to regulate negative emotions (Johns, Inzlicht, & Schmader, 2008), deleteriously impacts various indices of motor output, including balance ability in older adults, and the speed and accuracy of golf-putting and soccer dribbling in athletes (Lewthwaite & Wulf, 2010; Stone, Chalabaev, & Harrison, 2012). Additional indirect evidence for the vulnerability of motor output to depletion by executively-demanding activities, such as ES, comes from cognitive-motor interference (CMI) research, which demonstrates that simultaneous engagement in working memory and motor tasks deleteriously affects motor output (Fraser, Li, & Penhune, 2010; Nadkarni, Zabjek, Lee, McIlroy, & Black, 2010). Interestingly, the degree to which motor output is degraded by simultaneous engagement in working memory tasks (which rely on executive networks (Rottschy et al., 2012), but not by engagement in other, nonexecutive types of tasks, predicts functional outcomes (i.e., number of falls in a subacute stroke population; Bartnes et al. 2013). These findings provide further support for the unique association between motor output and EF, as well as for the notion that executively demanding tasks may results in degradation of motor performance.

However, because it is not clear which aspects of motor output are most strongly related to EF, it is also not clear which aspects of motor output are most susceptible to becoming degraded due to engagement in ES. There are at least two reasons to believe that different aspects of motor output may be affected differentially. First, Suchy and Kraybill (2007) have suggested that two aspects of motor output (i.e., action planning and action learning) may be more strongly related to EF than simple motor control (Suchy and Kraybill, 2007).[1] If the deleterious impact of ES on motor output occurs due to the close association between ES and EF, then those aspects of motor output that are more reliant on EF should exhibit the most deleterious impact. Secondly, past research shows that various aspects of motor output (action planning, action learning, motor-control speed, and motor-control accuracy) are differentially affected by experimental manipulations designed to interfere with performance. Two studies using an analogue of the PTT task demonstrated that manipulations designed to interfere with verbalization

[1] Though the association strengths were not directly compared statistically in this study.

(articulatory suppression and incongruent verbalization) exerted a consistent deleterious effect on participants' action learning and motor-control speed, and no impact on action planning or motor-control accuracy (Larson & Suchy, 2014a, 2014b).

Summary

Collectively, the research reviewed above suggests several key points. First, motor-output processes share considerable behavioral and neuroanatomical overlap with EF (Koziol, 2014; Mirelman et al., 2012; Ridler et al., 2006; Rigoli et al., 2012). In line with this notion, research demonstrates that motor sequence learning tasks, such as the PTT task, are clinically useful measures of EF that offer numerous benefits over more commonly used clinical measures (Kraybill & Suchy, 2011; Kraybill et al., 2013; Suchy et al., 2014; Suchy & Kraybill, 2007; Suchy et al., 2011). Second, both experimentally manipulated ES and naturally occurring fluctuations in ES are associated with a short-term cost in EF performance (Franchow & Suchy, 2015; Hofmann et al., 2012; Schmeichel, 2007). Third, there is some indirect evidence that motor output may also be negatively affected by ES (Baetens et al., 2013; Fraser et al., 2010; Lewthwaite & Wulf, 2010; Stone et al., 2012), though the effect of ES on motor sequence learning tasks has not yet been directly investigated. Finally, research demonstrates that different aspects of PTT performance (action planning, action learning, motor-control speed, and motor-control accuracy) are differentially affected by task demands designed to impair motor sequencing performance (Larson & Suchy, 2014a, 2014b). Taken together, these results suggest that higher than usual ES on the day of testing is likely to negatively impact some, but not all, aspects of performance on motor sequence learning tasks.

The Current Study

The current study investigated the impact of naturally occurring ES on PTT task performance. The primary aim was to investigate whether different aspects of motor sequence learning assessed by the PTT task (i.e., action planning, action learning, motor-control speed and motor-control accuracy) are affected by naturally occurring fluctuations in ES. A secondary aim of the current study was to examine whether any identified relationships between ES and motor output can be explained by EF.

Based on the research reviewed above, we generated two hypotheses for our primary aim. First, we hypothesized that individuals with high ES burden on the day of testing would display longer action planning latencies (action planning), lower accuracy rates (action learning), and longer motor-control speed, while motor-control accuracy would remain unaffected. Second, since Franchow and Suchy (2015) found that the association between ES and EF was only present for individuals who exhibited higher than usual ES burden on the day of testing, we predicted that *usual* ES burden (i.e., over the course of two weeks preceding testing) would moderate the relationship between motor output and the ES burden *on the day of testing*. Lastly, given that past research shows a strong, but not perfect, association between motor output and EF, it was not clear whether the deleterious impact of ES on motor output could be explained by EF, or whether ES would have a unique negative impact on motor output. Thus, we did not have a hypothesis for our secondary aim.

METHOD

Participants

Participants were 60 undergraduate volunteers from the University of Utah who received course credit in exchange for their participation.[2] Participants were screened for self-reported history of severe mental illness (e.g., psychotic disorders), any serious neurologic condition (e.g., seizure disorder, moderate to severe traumatic brain injury, hydrocephalus, etc.), or any serious medical condition known to affect the central nervous system (e.g., heart disease, diabetes, etc.). Consistent with past work on the deleterious impact of ES (Franchow & Suchy, 2015), participants who reported moderate to severe levels of depression (i.e., Beck Depression Inventory > 14) were excluded from the study (n=8). In addition, one participant was excluded due to outlying value on age (age=59). The final sample used for the principal analyses consisted of 51 students (female = 70.6%, right handed = 88.2%). The mean age of the sample is 23.14 years (SD=5.85, Range = 18-44) with an average education level of 13.63 years (SD = 1.47 Range = 11 - 17).

Procedures and Instruments

Informed consent was obtained from all participants and the University of Utah Institutional Review Board approved all procedures. As part of a larger study,

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[2] It should be noted that the current sample was previously used by Franchow and Suchy (2015) in a study demonstrating the association between the ES burden and EF. However, *no* motor output or PTT variables were examined in that study.

participants completed a 3-hour-long battery that included measures of motor sequence learning, EF, psychomotor speed, and depression.

Aspects of PTT Task Performance (Motor Sequence Learning)

To assess motor sequence learning, we used the Push-Turn-Taptap (PTT) task first introduced as part of the Behavioral Dyscontrol Scale—electronic version (Suchy, Derbidge, & Cope, 2005) battery. The task requires participants to learn a series of sequences involving three discrete movements (i.e., push, turn, and tap-tap) performed on a special response console. The sequences progress in length over the course of sequential blocks from a two-movement sequence to a five-movement sequence. Various aspects of performance (see below) are recorded electronically. In each block, participants are required to complete three correct trials while the sequence is displayed on the computer screen and then continue to complete the sequence from memory (i.e., after it disappears from the screen) until additional five correct consecutive trials are completed or until 10 trials have been attempted, whichever comes first (for a more detailed description of the task see Suchy & Kraybill, 2007). As was done in prior research (Kraybill & Suchy, 2011; Kraybill et al., 2013), scores for each aspect of performance were calculated across all blocks of the task. In order to assess the effect of ES on individual aspects of motor sequence learning, we computed four scores from the PTT task that align with the constructs of action planning, action learning, motor-control speed, and motor-control accuracy. As was done in our prior research (Larson & Suchy, 2014b; Suchy et al., 2010), action planning was operationalized as the median time between the completion of one sequence and initiation of the next. Action learning was operationalized as total number of errors (excluding double-tap perseverative errors).

Motor control was operationalized as the ability to perform a simple single movement smoothly and correctly, reflected in both the number of perseverative tapping errors (e.g., triple or quadruple taps) on the double-tap movement (accuracy) as well as the time between taps in the double-tap movement (speed).[3]

Executive Functioning (EF)

To assess whether ES affects PTT performance above and beyond EF, an EF composite was computed from a set of commonly used measures. Specifically, in keeping with prior research from our lab (Franchow & Suchy, 2015; Kraybill & Suchy, 2011; Kraybill et al., 2013), the EF composite was based on the following tasks from the Delis-Kaplan Executive Functioning System (D-KEFS): Trail Making Test (Letter Number Sequencing completion time), Design Fluency (total number of designs generated for each of the three conditions), Verbal Fluency (total words generated for each of the three conditions), and Color-Word Interference (Inhibition and Inhibition Switching total completion time). To generate a composite, all raw scores were converted to z-scores (variables were reversed as needed such that lower scores represented better EF) and the arithmetic mean across all nine z-scores was computed.

When assessing EF, it is critical to account for lower-order component processes that necessarily contribute to performance on any given EF task (Stuss, Picton, &

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[3] One participant had extreme number (over 4.5 SD above the mean) of motor-learning errors and motor-control errors on the 3rd block of the PTT. An additional participant had an extreme number (over 6.5 SD above the mean) of motor-learning errors on the first block, suggesting equipment malfunction on these two blocks. For these participants we computed prorated composites using a regression-based approach. Specifically, we predicted the values for all of the PTT variables on the problematic blocks using the other PTT variables that were most closely related to the needed scores. Action planning and motor-control speed scores were predicted using those same variables (e.g., action planning for action planning) on all remaining blocks. Motor-learning and motor-control accuracy errors were predicted using the errors scores on block two to predict block one and block four to predict block three.

Alexander, 2001). The D-KEFS battery is designed to control for some of the lower-order cognitive processes thought to contribute to EF, such as psychomotor speed, visual scanning, sequencing ability, and speed of verbal output (Homack, Lee, & Riccio, 2005). To ensure that our measure is truly a reflection of EF performance, we controlled for these component processes by computing a component process composite using the Trail Making Test (Visual Scanning, Number Sequencing, Letter Sequencing and Motor Speed completion times) and Color-Word Inference (Color Naming completion time).[4] This composite was also computed by converting raw scores to z-scores and taking the arithmetic mean of the five scores. As with the EF composite, lower scores represent better performance. To control for component processes, we computed the residuals of the EF composite after accounting for the component process composite score. The residuals were used as the principle EF variable of interest.[5]

Cronbach's alpha for the psychomotor speed composite and the EF composite in this sample was .72 and .77 respectively. The zero order correlation between these two composites in this sample was .51.

Depression

Depression was assessed using the Beck Depression Inventory, 2nd edition (BDI-II) (Beck, Ward, Mendelson, Mock, & Erbaugh, 1961). As noted above, participants with scores higher than 14 were excluded from the analyses, to avoid confounding our results

[4] Word Reading completion time from the Color-Word Interference subtest was not included because it lowered the reliability of the composite.

[5] For two participants we computed a prorated composite due to missing data resulting from experimenter error. One participant was missing conditions two and three on the Design Fluency subtest as well the completion time on the Inhibition Switching condition of the Color Word Interference subtest. The other participant was missing the Letter Sequencing condition from the trails subtest. Prorated composites for these participants were computed by taking the mean of available scores.

by the possible effect of depression on cognition (McDermott & Ebmeier, 2009). Cronbach's alpha in this sample was .91.

Burden of Expressive Suppression (ES)

Burden of ES was assessed using a set of 11 items (see Table 1) that ask about how much effort participants needed to control the expression of their emotions. Participants were asked to rate how much each of these items applied to them for two time periods: (a) over the course of the past 2 weeks leading up to testing and (b) on the day of testing. Participants answered on a five-point scale: *never* (0), *once or twice* (1), *sometimes* (2), *often* (3) *or all the time* (4). Two composite scores corresponding to ES over the course of the past 2 weeks (ES-2Weeks) and ES over the course of the day of testing (ES-Today) were computed. For additional details about the development of the measure and selection of items, see Franchow and Suchy (2015). For the current sample Cronbach's alpha was .78 and .80 for ES-Today and ES-2Weeks composites, respectively.

Table 1
Burden of Expressive Suppression

Item
1. I have made sure not to show my positive emotions.
2. I have made sure not to show my negative emotions.
3. I have forced myself to respond positively.
4. It has been difficult to maintain a neutral/pleasant facial expression.
5. It has been difficult to maintain an even tone of voice.
6. I have worked hard not to say what I was really thinking.
7. I have remained silent in order to keep myself from an angry outburst, or from saying something I didn’t mean.
8. I have worked hard to control, for example, impulses to throw or hit things.
9. I have had to work hard to control/moderate my breathing.
10. I have worked hard not to show I was scared.
11. It has been difficult not to blurt out something I was excited about (where it was inappropriate or interrupted someone else).

RESULTS

Preliminary Analyses

Descriptive statistics can be found in Table 2. Zero-order correlations among demographic variables, independent variables, and dependent variables can be found in Table 3. As can be seen, individual aspects of PTT performance were not all significantly related to each other, which supports the notion that they are dissociable and should be examined individually.

Also, as can be seen, the only aspect of PTT performance that was significantly related to the executive functioning composite scores was action planning. Consistent with our prior work on ES, and with our expectation that ES-2Weeks would moderate the relationship between PTT performance and ES-Today, no significant correlations were found between PTT performance and the ES-Today composite. This interaction was tested in the Principal Analyses.

Primary Aim Analyses

To determine whether self-reported burden of expressive suppression had a deleterious impact on aspects of PTT performance (as indices of motor sequence learning) we conducted a series of hierarchical regressions. Specifically, we tested four models assessing whether the relationship between reported level of expressive suppression on the day of testing and the four different aspects of PTT performance were moderated by self-reported level of ES burden over the past two weeks. Thus, as was done in our prior study (Franchow & Suchy, 2015), for each regression model BDI-II scores was entered on the first step as a covariate to control for possible effects of subclinical depression. ES-2Weeks was entered on the second step followed by ES-Today on step three. On the fourth and final step we entered an interaction between ES-2Weeks and ES-Today to determine if an individual's typical level of ES burden moderates the relationship between ES burden on the day of testing and PTT performance.

For action-planning latencies, the ES interaction term accounted for significant variance above and beyond BDI-II and the other two ES composite scores. Results from the hierarchical regression predicting action-planning latencies are reported in Table 4. In regression models with all four variables entered simultaneously as predictors, a significant positive main effect emerged for ES-Today (B=11.67, p=.015*).* This main effect was qualified by a significant interaction between ES-Today and ES-2weeks (B=.78*,* p=.045*).* To interpret this moderation effect, the interaction was de-composed by computing simple slopes[6] at one *SD* above the mean, at the mean, and at one *SD* below the mean of ES-2Weeks (Cohen, Cohen, West, & Aiken, 2003). This revealed that the association between ES-Today and action-planning latencies is stronger as ES-2Weeks decreases (low ES-2Weeks: B= 16.95, p= 0.007, average ES-2Weeks: B= 11.67, p= 0.015, high ES-2Weeks: B= 6.38, p= 0.154). Specifically, as seen in Figure 1, individuals who reported low ES burden over the past 2 weeks but high ES burden on the day of testing exhibited the longest action-planning latencies. In contrast, those with high ES burden over the course of the past 2 weeks seemed relatively unaffected by the ES

[6] Simple slopes were computed using the online utility (Preacher, Curran, & Bauer, 2006)

burden on the day of testing.

Additionally for motor-control accuracy and motor learning, BDI-II scores accounted for a significant amount of variance when entered as the only predictor in the models (*B*=.198, *p*=.044; *B*=.355, *p*=.018, respectively). This demonstrates a positive relationship between subclinical depression and accuracy during motor-sequence learning. The expressive suppression composites did not account for a significant amount of variance in the models predicting motor-learning and motor-control accuracy, all *p*-values greater than .11. Similarly, none of the predictors entered accounted for a significant amount of variance in the models predicting motor-control speed, all *p*-values greater than .43.

Secondary Aim Analyses

To determine whether any relationships observed between ES burden and action-planning latencies can be explained by EF, we repeated the hierarchical regression described above, this time with the EF composite entered as a covariate on step 1. As a reminder, the composite represents the residual variance in EF measures after accounting for the component process of psychomotor speed. The results of this model demonstrate that none of the ES variables nor BDI-II scores accounted for additional variance in action planning latencies above and beyond EF (see Table 5). This suggests the impact of naturally occurring ES on action planning can be completely explained by EF.

Table 2
Descriptive Statistics for Expressive Suppression, PTT Performance, and Executive Functioning Composites

Variable	Mean (*SD*)	Range
ES-Today	6.37 (6.27)	0-26
ES-2Weeks	10.57(6.84)	0-29
Action Planning (msec)	722.71 (148.27)	433.78-1020.88
Action Learning (# of errors excluding double tap errors)	4.45 (3.80)	0-18
Motor-control Speed (sec)	250.04 (53.39)	153.38-420.63
Motor-control Accuracy (# of double tap errors	3.65 (2.46)	0-12
Executive Functioning (after accounting for Psychomotor Speed)	.000 (.51)	-1.14-1.20

Note. N=51. ES-Today = expressive suppression on the day of testing; ES-2Weeks = expressive suppression over the past 2 weeks; Executive Functioning (Accounting for Psychomotor Speed) = Residuals after regressing the executive functioning composite onto the psychomotor speed composite; Action Planning = Latencies (in msec) between correct sequences on the PTT task; Action Learning= Total number of PTT errors excluding double tap errors; Motor-control Accuracy= Total number of PTT double tap errors.

Table 3
Zero Order Correlations among Independent and Dependent Variables and Demographic Data

	Action Planning	Action Learning	Motor-control Speed	Motor-control Accuracy
Age	.097	-.033	-.012	-.133
Education	.198	-.152	.174	-.352*
Depression	.127	.329*	.090	.283*
ES-Today	.259	.031	-.077	.186
ES-2Weeks	.141	.078	.045	.334*
Psychomotor Speed	.294*	.008	.109	.052
Executive Functioning	.635**	.169	.151	.004
Executive Functioning (Accounting for Psychomotor Speed)	.564**	.192	.111	-.026
Motor-control Accuracy	.131	.619**	-.020	1
Motor-control Speed	.446**	-.275	1	
Action Learning	.020	1		

Note. N=51. *=*p*<.05 (two-tailed), **=*p*<.01 (two-tailed). Depression = Total score on the Beck Depression Inventory-Second Edition; ES-Today = expressive suppression on the day of testing; ES-2Weeks = expressive suppression over the past 2 weeks; Psychomotor Speed = Psychomotor speed composite scores; Executive Functioning = Executive functioning composite scores; Executive Functioning (Accounting for Psychomotor Speed) = Residuals after regressing the executive functioning composite onto the psychomotor speed composite; Action Planning = Latencies (in msec) between correct sequences on the PTT task; Action Learning= Total number of PTT errors excluding double tap errors; Motor-control Accuracy= Total number of PTT double tap errors.

Table 4
Hierarchical Linear Regression Predicting Action Planning Latencies by Expressive Suppression

Step	Variable	R^2	$R^2\ \Delta$	$F\ \Delta$	*df*	*p*
1	Depression	.016	.016	.805	1,49	.347
2	ES-2Weeks	.021	.005	.235	1,48	.630
3	ES-Today	.089	.068	3.497	1,47	.068
4	ES-Interaction	.166	.077	4.231	1,46	.045*

Note. *N*=51, Depression = Total score on the Beck Depression Inventory-Second Edition ES-Today = expressive suppression on the day of testing; ES-2Weeks = expressive suppression over the past 2 weeks; ES Interaction = ES-Today x ES-2Weeks; * $p < .05$ (two-tailed) **= $p < .01$ (two-tailed).

Table 5

Hierarchical Linear Regression Predicting Action Planning Latencies by Expressive Suppression and Executive Functioning

Step	Variable	R^2	$R^2\,\Delta$	$F\,\Delta$	*df*	*p*
1	EF	.318	.318	22.887	1,49	>.001
2	Depression	.328	.010	.699	1,48	.407
3	ES-2Weeks	.334	.006	.428	1,47	.516
4	ES-Today	.346	.012	.835	1,46	.365
5	ES-Interaction	.351	.005	.322	1,45	.573

Note. N=51, Depression = Total score on the Beck Depression Inventory-Second Edition EF = executive functioning composite, ES-Today = expressive suppression on the day of testing; ES-2Weeks = expressive suppression over the past 2 weeks; ES Interaction = ES-Today x ES-2Weeks; * $p < .05$ (two-tailed) **= $p < .01$ (two-tailed).

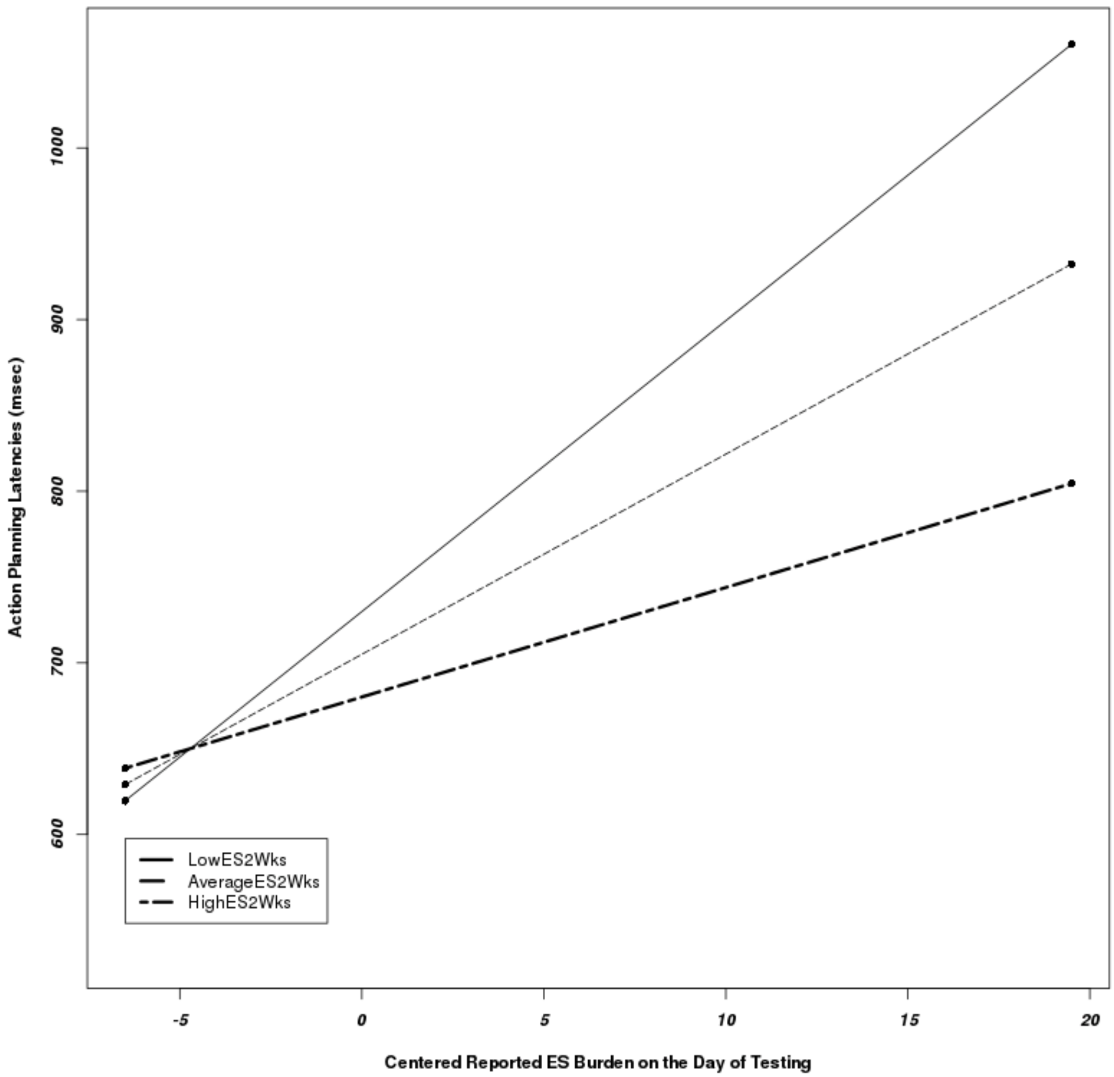

Figure 1.
This figure illustrates that the relationship between self-reported expressive suppression scores on the day of testing and action planning latencies at different levels of self-reported expressive suppression scores over the two weeks leading up to testing. Simple slopes are shown for low (one *SD* below the mean) medium (the mean) and high (one *SD* above the mean) levels of self-reported expressive suppression over the two weeks leading up to testing.

DISCUSSION

The current study aimed to bridge two literatures that have largely been developing in parallel: the literature establishing the functional and neuroanatomical overlap between EF and various aspects of motor output (Koziol, 2014; Kraybill & Suchy, 2011; Mirelman et al., 2012; Ridler et al., 2006; Rigoli et al., 2012; Suchy & Kraybill, 2007; Suchy et al., 2010), and the literature demonstrating that recent engagement in ES leads to decreased performance on executively demanding tasks (Baumeister & Alquist, 2009; Bray et al., 2011; Fischer et al., 2012; Franchow & Suchy, 2015; Inzlicht & Gutsell, 2007; Muraven et al., 1998). Collectively, this work suggests that higher-than-usual ES burden is likely to be associated with decreased performance on aspects of motor output that rely on EF. To test this hypothesis, the current study (a) investigated the relationships between different aspects of motor sequence learning assessed by the PTT task (i.e., action planning, action learning, motor-control speed and motor-control accuracy) and self-reported ES burden, and (b) examined whether any identified relationships could be explained by EF.

Results confirmed our hypothesis that higher-than-usual self-reported ES burden (increased on the day of testing relative to the two weeks preceding testing) would be associated with longer action planning latencies. However, contrary to expectation, no other assessed aspects of motor output were associated with ES burden on the day of testing. Importantly, self-reported ES burden did not account for variance in action planning latencies above and beyond EF performance, suggesting this effect can be explained by depletion of EF rather than its own unique pathway.

Ramifications for Daily Life

The present findings may also have particularly meaningful ramifications for daily life. Action planning is the process by which internal models for action are generated (Buxbaum, Johnson-Frey, & Bartlett-Williams, 2005) and individual movement elements are bundled together into a single motor program that can then be fluidly executed (Baldauf, 2011). Efficient action planning is thought to facilitate successful navigation around obstacles while walking, as it allows individuals to quickly reprogram new action trajectories when presented with unexpected changes in their environment (Knobl, Kielstra, & Almeida, 2012; Uemura, Yamada, Nagai, & Ichihashi, 2011). Depletion of action planning resources due to excessive ES burden could then be associated with poor obstacle navigation, which in turn could lead to falls. In fact, indirect support for this notion already exists. For example, factors that deplete the cognitive resources needed for action planning, such as completing an executively demanding dual task, have been shown to produce more errors during obstacle navigation (Chen et al., 1996; Menant, St George, Fitzpatrick, & Lord, 2010).

Importantly, this effect appears to be amplified for older adults and individuals with Parkinson's disease (Chen et al., 1996; Pieruccini-Faria, Ehgoetz Martens, Silveira, Jones, & Almeida, 2014), which may partially explain the relatively high prevalence of falls in these populations (Hill, Schwarz, Flicker, & Carroll, 1999; Pieruccini-Faria et al., 2014). Relatedly, older adults with a history of falls have also been shown to be slower and less efficient in the planning stages of obstacle navigation (i.e., making postural adjustments before crossing an obstacle) (Uemura et al., 2011). Therefore, future research should examine whether daily fluctuations in ES burden are related to increases in falls, as well as directly test whether obstacle navigation errors are more common following increases in ES burden.

Is Action Planning Uniquely Depletable?

One explanation for why action planning was uniquely related to reported increased ES burden is that it is simply ‘more vulnerable’ to cognitive stressors than the other aspects of performance. This is unlikely, however, as two past studies designed to interfere with verbalization documented a consistent negative impact on motor learning and speed of motor control, but no effect on action planning (Larson & Suchy, 2014a, 2014b). This difference may appear counterintuitive, as the tasks used in these studies (i.e., articulatory suppression and incongruent verbalization) tax verbal-working memory (Baddeley, Chincotta, & Adlam, 2001), a process thought to be subsumed under the EF umbrella (Suchy, in press). However, in our recent work, we have demonstrated that both behavioral and neural indices of action planning were significantly related to a comprehensive EF composite, but *not* to working memory (Euler, Niermeyer, & Suchy, 2015). Together, these findings suggest that action planning and working memory may represent two distinct components of EF, as we have previously argued (Suchy, in press). Consequently, different types of cognitive stressors may impact different aspects of EF, which in turn impair different aspects of motor output.

In the current study action planning was the only aspect of performance significantly related to EF. This likely explains why action planning was the only aspect of performance associated with increased ES on the day of testing. This finding was somewhat surprising, however, as past work with the PTT task has documented that action planning, action learning, and motor control are all significantly related to EF (Suchy & Kraybill, 2007). One possible explanation for this discrepancy is that the components of motor sequence learning that rely on EF, and subsequently are affected by excessive ES, may change as a function of age. In fact, there is behavioral evidence that motor sequencing becomes more reliant on EF with increasing age (Fraser et al., 2010). Neuroimaging studies also show greater activation of the frontal cortices among older as compared to younger adults during motor coordination and action planning tasks (Berchicci, Lucci, Pesce, Spinelli, & Di Russo, 2012; Heuninckx, Wenderoth, & Swinnen, 2008). Thus, although Suchy and Kraybill (2007) found that all aspects of motor sequence learning are related to EF, their sample was comprised of age groups across the adult lifespan. This marks an important difference from the current study, which recruited participants from an undergraduate (i.e., young adult) population.

In addition, Larson and Suchy (2014a) used children as participants in their study of the impact of incongruent verbalization on motor output, and once again it is possible that age differences between that and the present study may have contributed to the discrepant findings. Neuroimaging studies show that higher-order cognitive abilities and motor abilities in children both rely on the development of an overlapping set of neural regions including frontal, parietal, cerebellar and basal ganglia structures (Pangelinan et al., 2011; Ridler et al., 2006). These areas rapidly develop during childhood (Pangelinan et al., 2011), and this ongoing development could cause various aspects of motor output to be differentially vulnerable to interference or depletion in children, versus adults.

It is unlikely, however, that the differences in the results between the verbalization studies and the current study can be entirely explained by age differences, as Larson and Suchy (2014b) used a college population in their study of the impact of articulatory suppression on motor output. Another likely factor contributing to the discrepant results across these studies are differences in task demands. The analogues of the PTT task used by Larson and Suchy (2014a,b) both required participants to perform only one specific sequence of hand movments. Additionally, the tasks used in these studies included a separate learning and perfomance phase. In the current study participants performed a series of movement seqeunces of increasing length across four blocks without an extensive learning period. These task differences may have changed the neurocogntive processes needed for sucessful completion of various aspects of the task. For example, using the same seqeunce may have made action planning less related to working memory because participants no longer needed to mentally rehearse the order of the movements. This is consitent with our recent research showing that aciton planning is less stronlgy related to EF for sequences in familiar, versus novel, contexts (Euler et al., 2015), and with neuroimaging research showing progressively less activation in the prefrontal, sensorimtor, and parietal corticies responsible for action planning as a motor task becomes more automatic (Floyer-Lea & Matthews, 2004).

Taken together, these results suggest that the aspects of motor output negatively impacted by a cognitive stressor are likely to vary as a function of (a) the type of cogntive stressor, (b) population characteristics, and (c) specific task deamands. The studies reviewed above also highlight the susceptibility of motor output to depleted cognitive resources.

Ramifications for Neuropsychological Assessment

In clinical assessments, accurate measurement of EF, including action planning, has important implications both diagnostically and for predicting future functional outcomes (Lezak et al., 2012; Robinson et al., 2002). Additionally, in a research context, EF assessment is becoming increasingly prominent in a diverse number of fields (Suchy, 2009). Taken together with past research, the findings from the current study suggest that researchers and clinicians should take into account and adjust for stressors in daily life that deplete EF, to maximize the accuracy of their assessment. In order to do this effectively, psychometrically validated tools are needed that can reliably and efficiently capture factors like increased ES burden. Further psychometric development of the measure used to assess ES burden in the current study is therefore warranted. In addition, the extent of individual differences in how *resilient* an individual's EF is when faced with increased ES burden also merits future study.

Limitations

The current study has some limitations that should be noted. As noted in Franchow and Suchy (2015), self-report measures are necessarily limited by participants' memory, self-insight, and tendency to present themselves in a socially desirable manner. Future validation work is needed and should include the examination of individual differences in response style and the development of response validity measures.

Additionally, the goal to investigate self-reported ES burden necessitated the use of a correlational design. As a result we cannot determine whether fluctuations in ES burden are causally related to longer action planning latencies. Future studies could begin to address this limitation using a number of different methodologies. For example, a conceptual replication and extension of the current findings could assess whether experimentally manipulated ES selectively interferes with action planning latencies rather than other aspects of motor output. Also, similar to the argument outlined by Franchow and Suchy (2015), another way to begin to test causal relationships among naturally occurring fluctuations in ES, EF, and action planning would be to establish a baseline of these variables for a sample and then assess changes over time.

Another potential limitation of the current study related to the correlational design is that the participants who rated themselves as having increased burden of ES over the course of the day of testing may be experiencing more stressful events or other experiences that might coincide with or be driving their increased need for emotion regulation. A complete assessment of the reasons driving the self-reported increased ES burden and other coinciding stressors was beyond the scope of the current study. However, future work that isolates and accounts for the potential contribution of other variables, such as decreased sleep and increased stress level, would help to clarify the current findings. That being said, the deleterious impact of ES has previously been demonstrated in the experimental literature (Baumeister & Alquist, 2009; Bray et al., 2011; Fischer et al., 2012; Inzlicht & Gutsell, 2007; Muraven et al., 1998), suggesting it is unlikely that these other variables would fully account for the current findings.

The use of the PTT task was a strength of the study in many ways. Namely, this task allowed for the precise measurement of discrete aspects of motor output, as well as the ability to draw on existing literature establishing the task's reliability, validity, and promising clinical utility (Kraybill & Suchy, 2011; Kraybill et al., 2013; Suchy et al., 2005; Suchy & Kraybill, 2007). However, the use of the PTT task may also limit the generalizability of the findings. For example, the results may not apply to overlearned action tasks. Our recent work demonstrated that action planning latencies during the performance of a familiar sequence were only significantly related to EF if the sequence was presented in a novel context (Euler et al., 2015). This suggests that ES is likely to have the biggest effect on action planning when individuals are planning a novel movement or a familiar movement in a novel context. Future studies should investigate this empirically. Also, while the PTT task has more psychometric support than many tasks used in experimental settings, the lack of population-based norms makes it somewhat difficult to determine the practical or clinical significance of the prolonged action planning time. Future studies may consider using measures of various aspects of motor output that are normed for healthy and clinical populations in order to provide further clarification of the significance of the depletion effect on action planning.

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