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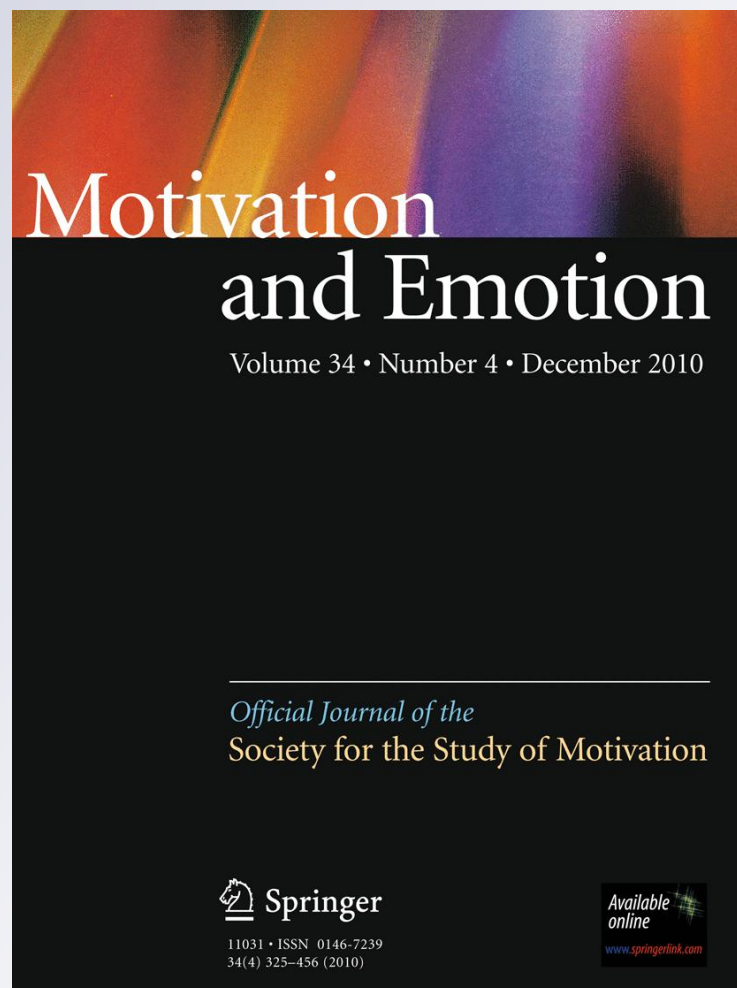
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Subclinical depression modulates the impact of emotion on force control

Kelly M. Naugle · Stephen A. Coombes ·
Christopher M. Janelle

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Abstract The primary goals of this project were to examine whether (1) the impact of emotional state on force control varies as a function of target force level, (2) self reports of emotional state covary with force control, and (3) emotional state and trait levels of depression interact to alter force control. Subjects varying in self-reported depression performed a sustained pinch grip for 20 s at low, moderately low, and moderate target force levels. Each trial began with 8 s of visual feedback, which was replaced with an emotional or neutral image for 12 s. Subjects reported valence and arousal ratings for each image. Across the entire sample, self-reported arousal predicted constant error (CE) during low and moderately low target force trials. Depression significantly predicted the relationship between self-reported valence and CE during moderate target force trials. Theoretical explanations, implications, and future research directions are discussed.

Keywords Depression · Emotional states ·
Motor performance

The ability to efficiently and effectively execute intended motor behaviors is of paramount importance for achieving virtually all goal directed human endeavors. In everyday life, the execution of functional tasks typically co-occurs with emotional reactions to events unrelated to the

functional task being performed (e.g., driving while simultaneously arguing or laughing with a passenger). In addition, evidence has shown that bipolar disorder (Lohr and Caligiuri 2006) and subclinical depressive symptoms (Oathes and Ray 2006) coincide with abnormalities in motor function, and these abnormalities can lead to fatigue, frustration, and performance failure. The goal of the current study was to examine the relation between emotional state, subclinical depression, and force production.

The biphasic theory of emotion suggests that emotion is regulated by two motivational systems that adaptively respond to appetitive and aversive stimuli (Lang et al. 1998). Typically, the appetitive system is associated with pleasant emotion and directs approach-related behavioral responses while the defensive system is associated with unpleasant emotions and directs withdrawal-related behavioral responses. Thus, emotion can be organized by two dimensions: valence (pleasant, unpleasant) and arousal (intensity of activation of each system). The biphasic organization of emotion has provided the bases for much of the previous emotion and movement research which has demonstrated that affective valence and motivational direction influence approach and avoidance movements (Chen and Bargh 1999; Coombes et al. 2007a, b, 2009). However, many functional tasks that require precise force control are ambiguous in terms of movement direction (i.e., applying force to hold a coffee cup). Indeed, previous evidence has demonstrated that emotional arousal rather than emotional valence influences grip force control (Coombes et al. 2008; Schmidt et al. 2009).

Arousal, force control, and target force level

Threat of shock, which is thought to elicit an unpleasant emotions, increases the variability of force output

K. M. Naugle (✉) · C. M. Janelle
Department of Applied Physiology and Kinesiology,
University of Florida, 100 FLG, P.O. Box 118205,
Gainesville, FL 32611, USA
e-mail: kmgamble@hnp.ufl.edu

S. A. Coombes
University of Illinois at Chicago, Chicago, USA

(coefficient of variation: CV) at extremely low target force levels [i.e., ~2–4% of maximum voluntary contraction (MVC)] when visual feedback of the movement is occluded (Christou 2005). Because a highly arousing pleasant condition was not manipulated in these previous studies it is not clear whether the arousal or the valence of the emotional state drove the alterations in motor output. Coombes and colleagues (2008) used a pinch-grip task at a moderately low target force level (10% of MVC) to examine the effect of pleasant, unpleasant, and neutral images on force control. A relative increase in force production was evidenced during exposure to pleasant and unpleasant as compared to neutral images, suggesting that emotional arousal rather than emotional valence influences grip force control. The effect of emotional arousal rather than emotional valence on grip force has been corroborated by evidence using a short duration maximal power grip task (Schmidt et al. 2009). These collective findings suggest that emotional arousal influences grip force production. However, the required force level, the duration of force production, and the grip formation (power, pinch) varied across these previous studies. Our first goal was therefore to examine the impact of emotional arousal and emotional valence on force control at varying levels of force amplitude while holding grip formation and duration of force constant.

Self-reported emotional reactivity and overt behavior

Evidence shows that self-reported valence and arousal judgments of IAPS pictures covary with psychophysiological responses (Bradley et al. 2001). For instance, skin conductance responses vary with self-reported emotional arousal, whereas corrugator EMG activity, heart rate, and the startle eye blink reflex vary with self-reported valence (Bradley et al. 2001). Although overt behavior is considered one of three emotion response systems (along with self-report and physiological processes), it is not yet clear whether self-reported ratings of valence and arousal systematically covary with overt motor behavior. The second goal of the current study was to determine whether self-reported levels of emotional arousal and valence are associated with motor output, and if this relationship remains consistent at varying target force levels.

Subclinical depression and emotional reactivity

Depressed individuals show reliable and distinct differences in emotional reactivity as compared to non-depressed individuals. For example, depressed individuals display blunted startle reflex responses while viewing pleasant pictures (Larson et al. 2007) and experience a long lasting

dampening (>4 s) of event-related potentials (ERP) during the processing of positive self-relevant information, but intact ERPs to unpleasant and neutral stimuli (Shestyuk et al. 2005). In addition, they fail to show the expected increase in zygomatic EMG activity to happy facial expressions (Sloan et al. 2002), and exhibit reduced frequency and intensity of facial expressions to pleasant but not unpleasant stimuli (Sloan et al. 2001). Depression has also been associated with interhemispheric differences in motor threshold potentials and resting state asymmetry measures, with individuals relatively higher in depression exhibiting lower excitability of the left frontal region (Lefaucheur et al. 2008).

The psychomotor sequelae of depression are subtly present in the DSM-IV. Diagnostic criteria for Major Depressive Disorder (MDD) include psychomotor slowing (retardation), with rates of agitation and slowing ranging from 46 to 67% (Sobin and Sackeim 1997). Features of motor slowing include reduced movement speed, delayed motor initiation, body immobility, and postural abnormalities (Parker et al. 1993). Potentially problematic to the treatment of depression, these psychomotor symptoms are only subjectively assessed by clinicians. Objective measures have been used to demonstrate that patients with MDD exhibit slower reaction times and lower peak movement velocities on a wrist rotation task as compared to healthy participants (Caligiuri and Ellwanger 2000). Depressed individuals also exhibit lower levels of motor cortex activity while performing an elbow flexion contraction, and this has been attributed to a reduced ability to drive the motor cortex (Loo et al. 2008). Requiring elbow flexion at maximal exertion exacerbated this effect in the motor cortex. Motor abnormalities have also been observed in individuals with subclinical levels of depression. Oathes and Ray (2006) used transcranial magnetic stimulation (TMS) to demonstrate that while at rest, individuals with more depressive symptoms produced less force in the index finger following stimulation to the primary motor cortex relative to less depressed individuals. Converging evidence, therefore, shows that individuals with higher levels of clinical and subclinical depression exhibit blunted emotional responses to pleasant cues, as well as disrupted motor functioning. How emotional reactivity and trait levels of depression interact to alter motor behavior has yet to be systematically investigated. The third goal of the current study was to address this gap in the literature.

The present study used traditional general linear modeling (GLM: ANOVA) and advanced hierarchical linear modeling (HLM) statistical analyses to test three hypotheses. First, increases in emotional arousal were predicted to similarly affect force production across varying levels of motor system activation. Second, self-reported levels of emotional valence/arousal were hypothesized to be related

to changes in force production. Third, changes in emotional reactivity to emotional stimuli were expected to be reflected in force production alterations that differed as a function of subclinical depression.

Methods

Subjects

Eighty-six undergraduate students volunteered to participate in the study. Twelve subjects who did not complete the Self-Assessment Manikin (SAM) instrument properly (same arousal and valence rating given for all images) and 10 subjects with missing BDI and/or STAI scores were removed from analyses. Additionally, eight left-handed subjects were also excluded from the analyses to avoid a potential confound of hand dominance. We also removed individual outlier trials defined as individual trials exceeding three standard deviations from the means of the dependent variables before the analyses. No more than one trial for each valence condition at each target force level was removed for each subject. Additionally, each subject had no more than three total trials removed (i.e., across all subjects 28 total trials were removed; less than 1% of the data). In sum, 56 right-handed subjects, reporting no central nervous system disorders that would affect movement and corrected or corrected to normal vision, were included in the final statistical analyses. Per our objective of selecting a sample of subclinically symptomatic subjects, they reported a mean of 7.96 (5.28) on the Beck Depression Inventory (Beck and Steer 1987). See Table 1 for all demographic data.

Instrumentation and task

Subjects performed a sustained isometric contraction by pinching a force transducer (MLP-75, transducer techniques, Temecula, CA, USA) with the thumb and index finger of their dominant hand. The force transducer (75 kg; 1.3 cm wide) had a sensitivity of 0.1%. Analog output from the force transducer (sum of the thumb and index finger force) was amplified through a 15LT Grass Technologies Physiodata Amplifier System (Astro-Med Inc., West

Warwick, RI, USA) at an excitation voltage of 10 V. Custom LabVIEW software controlled a 16-bit analog-to-digital converter (A/D) (PCI-6220, National Instruments, Austin, TX) which sampled the force at 100 Hz.

Prior to the practice and experimental trials, subjects' MVC was measured according to a well established method (Vaillancourt and Newell 2003). Specifically, participants were required to squeeze as hard a possible on a force transducer for three 6 s trials with 60 s rest periods between each trial. The greatest 10 force samples from each trial were averaged. The means of the three trials were then averaged to compute the MVC value. The MVC value was then used as the reference for computation of each target force of interest for each individual. Visual feedback of force production for the pinch grip task was presented on a computer monitor that displayed two bars. A black stationary horizontal bar (which was positioned at 2, 10, or 35% of MVC) located center screen represented the target force level, and a white horizontal bar represented the amount of force being produced by the subject. Subjects were instructed to alter their force production level (white bar) to match that of the black target bar. Subjects sustained this level of force production as accurately as possible throughout the 20 s trial in the presence or absence of visual feedback (See Fig. 1 for experimental protocol). Subjects completed three blocks of 18 trials. In each block subjects performed the pinch grip at low (2% of MVC), moderately low (10% of MVC), and moderate (35% of MVC) target force levels (six trials at each force level). Visual gain was held constant at 25 pixels per N for all conditions.

Emotion manipulation

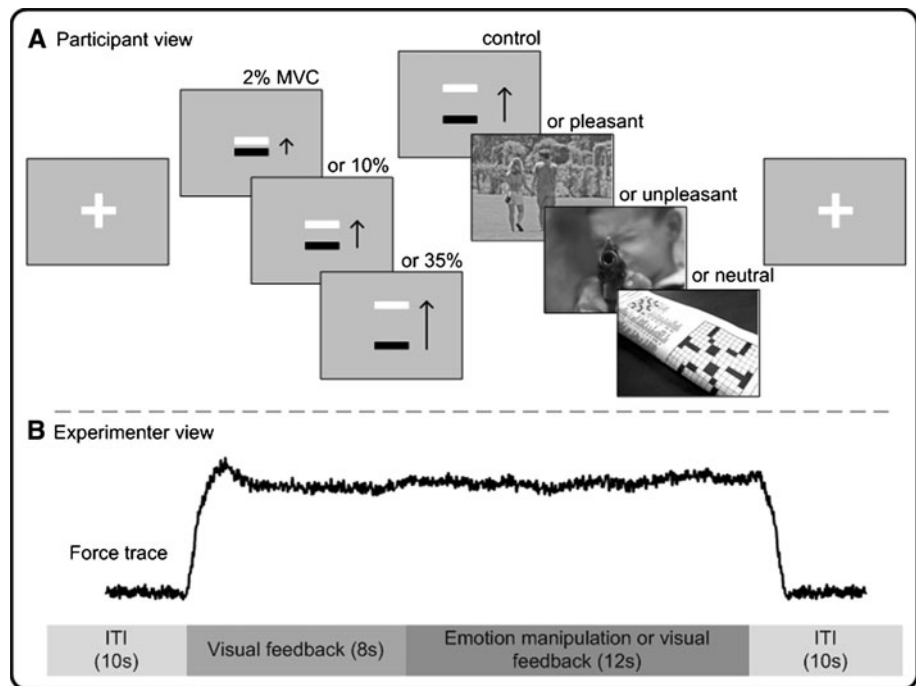
On 36 of the 54 experimental trials (12 of the 18 trials in each block), visual feedback was occluded after 8 s with a digitized image selected from the IAPS (Lang et al. 2005), representing one of four affective categories: (1) erotic couples, (2) attack, (3) mutilation, and (4) neutral.¹ Each valence category was presented three times per block. The IAPS image covered the entire screen for 12 s. The images were chosen in accord with affective normative ratings. Valence was differentiated across all categories, while pleasant and unpleasant images were matched for arousal, distinguishing each from neutral images. Three trials per block were completed with constant feedback and no picture (control condition) and three trials per block were completed with no feedback and no picture. Stimulus

Table 1 Subject characteristics

	Males (<i>n</i> = 22) Mean (SD)	Females (<i>n</i> = 34) Mean (SD)
Age	20.73 (1.08)	19.94 (1.08)
MVC (N)	55.65 (12.95)	44.61 (9.75)
Trait anxiety (STAI)	35.73 (9.83)	36.29 (8.68)
Depression (BDI)	7.41 (4.61)	8.17 (5.71)

¹ Erotic couples: 4670, 4652, 4658, 4659, 4311, 4687, 4695, 4664, 4800; Attack: 6313, 6350, 3530, 6230, 6510, 3500, 6560, 6550, 6260; Mutilation: 3168, 3071, 3060, 3130, 3016, 3000, 3069, 3010, 3225; Neutral: 7140, 7025, 5731, 7055, 7040, 7100, 7052, 7217, 7235.

Fig. 1 Experimental protocol. Participants were required to maintain their target level of force production (2, 10, or 35% MVC) as accurately as possible during the entire 20 s trial. On all trials, visual feedback was presented for the initial 8 s. During control trials feedback remained on the screen for the remaining 12 s. During feedback occlusion trials, feedback was replaced with an IAPS image



presentation order and target force level were randomized in each block so that no two conditions and target force level were performed consecutively. Blocks were counterbalanced across subjects.

Procedure

The Institutional Review Board at the University of Florida approved all experimental procedures. Upon arriving at the laboratory subjects signed a written informed consent and completed the Trait form of the State Trait Anxiety Inventory (STAI; Spielberger 1983) and Beck Depression Inventory (BDI; Beck and Steer 1987). Having completed the necessary MVC trials, subjects were instructed through the main component of the experiment. Each trial began with the appearance of the black and white bars on the screen. The appearance of these bars cued subjects to execute and sustain the amount of force necessary to match their own force level (black bar) with the target force bar (2, 10, 35% of MVC), and to do so as accurately as possible for the entire trial. Subjects executed eight practice trials (three feedback only trials, two no feedback trials, and 1 trial at each target force level with unique neutral images). After all questions had been answered, the experimenter left the room and subjects completed three blocks of 18 experimental trials. Trial offset was marked with the word “Relax” located in the center of a blank screen. Intertrial intervals lasted 10 s. After each block and for each picture previously viewed in that block, subjects completed a computerized 9-point version of the SAM to obtain

subjective ratings of valence and arousal (Bradley and Lang 1994). Subjects viewed and rated a total of 36 pictures.

Data reduction

The force–time series data were digitally filtered with a fourth-order Butterworth filter with a 20 Hz low-pass cut-off. Constant error (CE) and coefficient of variation (CV) were calculated and analyzed during the 12 s of picture presentation of each trial.

CE

CE indicates the direction of error relative to the target force. For each data point the vertical distance between the target force and the amount of force being produced was calculated. Each 1 s epoch consisted of 100 samples and CE was computed by taking the mean of these 100 samples. A positive value indicates an increase in force production relative to the target. A negative value indicates a decrease in force production relative to the target.

CV

CV represents the variability of force around its mean. CV scores were calculated and analyzed to ensure that variability was normalized to the magnitude of the corresponding absolute force value ($CV = SD/\text{mean force}$).

To replicate previous emotion and force control research (Coombes et al. 2008) and to test hypothesis 1, force data were analyzed using general linear modeling analyses of variance (ANOVA) as a preliminary analysis. As our primary analysis and to test hypotheses 2 and 3, we then used Hierarchical Linear Modeling (HLM) to extend this work and obtain a more comprehensive portrayal of the impact of state and trait affective variables on force output. In particular, HLM allowed us to assess both within subject and between subject differences in force output, as well as whether the between subject differences predicted the within subject differences. The HLM procedure is described at the beginning of the primary analysis section.

Preliminary analyses and results

SAM

SAM data were analyzed to determine differences in the self-reported valence and arousal ratings between the four picture categories. A one-way ANOVA indicated a significant effect of category for valence rating, $F(1.72, 112.44) = 221.77$, $p < .001$. Subjects rated (1) erotica images as more pleasant than mutilation, attack and neutral images, (2) mutilation images as more unpleasant than attack and neutral images, and (3) attack images as more unpleasant than neutral images. We also found a significant effect of category for the arousal ratings,

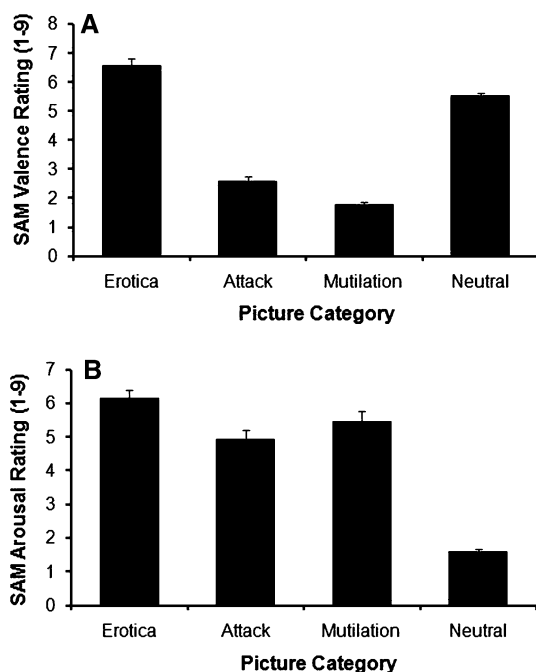


Fig. 2 a Mean SAM valence ratings for each IAPS picture category. b Mean SAM Arousal ratings for each IAPS picture category

$F(2.30, 145.01) = 113.09$, $p < .001$; Erotica > mutilation > attack > neutral. See Fig. 2.

Force data

Force data were initially analyzed using general linear modeling analyses of variance (ANOVA). Planned comparisons were performed on each target force level 1 s prior to picture onset (baseline: to ensure similar performance prior to emotion manipulation) and the last second of picture onset (to compare with prior work) with 1-way ANOVAs (Valence). The baseline analyses demonstrated that within each target force level force production was similar between valence conditions prior to image onset (all p 's > 0.05).

Figure 3 shows mean CE across the 12-s viewing period for each valence category when the target force level was set at 2% (A), 10% (B) and at 35% (C) of MVC. All scores were normalized to demonstrate the pattern in force production across the different force levels.

Constant error: 2% of MVC (see Fig. 3a)

A significant main effect of valence on force production was identified when the target force level was set at 2% of MVC, $F(4.13, 268.69) = 10.46$, $p < 0.001$. Follow-up tests showed that error during the feedback condition was attenuated relative to all conditions in which feedback was occluded. As shown in Fig. 3a, the presentation of feedback ensured the maintenance of a stable force amplitude. However, when feedback was occluded, force production increased above the target line, a finding that was exaggerated during the more arousing conditions (erotica, mutilation, attack) relative to the less arousing neutral condition. The presentation of erotica images also resulted in greater error compared to the no feedback condition.

Constant error: 10% of MVC (see Fig. 3b)

A significant effect of valence was evidenced when the target force level was set at 10% of MVC, $F(4.67, 230.91) = 26.88$, $p < 0.001$. The presence of feedback ensured that force output was matched to the required target force level. This was not the case during feedback occlusion conditions, however, with force output showing a progressive decrease across time. Greatest decay in force output was evidenced during the no-feedback condition relative to all other conditions with a general arousal pattern emerging in a similar manner to the findings at the 2% target force level. That is, least error was evidenced during the most arousing erotica and mutilation conditions as compared to lesser arousing conditions (erotica = mutilation < attack = neutral < no feedback).

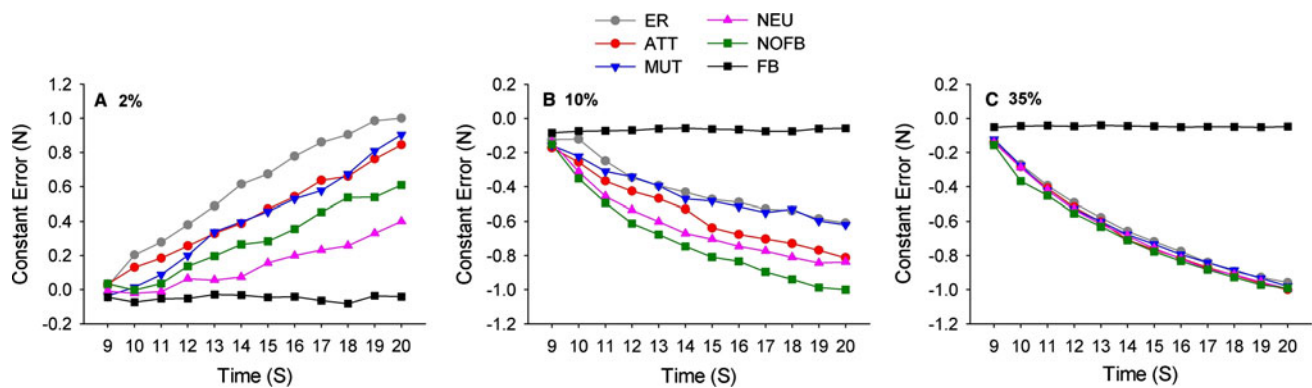


Fig. 3 Mean CE for each target force level as a function of valence category across time (beginning 1 s prior to image onset)

Constant error: 35% of MVC (see Fig. 3c)

Finally, although a significant effect of valence was identified at 35% of MVC, $F(2.62, 170.30) = 204.03$, $p < .001$, follow-up tests revealed that the force produced during the visual feedback condition only resulted in less error relative to all conditions in which feedback was occluded.

Coefficient of variation

No significant effects of valence were found at 2% of MVC. At 10% of MVC, a significant effect of Valence ($F(4.06, 263.56) = 5.068$, $p = 0.001$) revealed that variability was attenuated during the feedback condition relative to all other conditions. A significant effect of valence was also found at 35% of MVC [$F(3.28, 213.44) = 6.94$, $p < .001$]. At this moderate force level, variability was (1) reduced while viewing erotica images relative to attack and neutral images, and (2) attenuated during the feedback conditions compared to all other conditions.

Primary analyses and results

Our study produced a multilevel data set in which trial-level data were nested within subject-level data. We were interested in the data acquired during the 12 s of picture presentation. HLM (Raudenbush et al. 2005) was used to examine: (1) the effect of self-reported arousal and self-reported valence on movement outcomes, (2) the effect of subclinical depression on movement outcomes, and (3) the moderating effect of subclinical depression on the level-1 effects (i.e., cross-level interaction), while controlling for trait anxiety and MVC.

The data were nested in a “person-trial,” nesting the level-1 movement outcome variables in the level-2 person

variable ($n = 56$). The focus of the analyses was on how the emotion induction, measured by the valence and arousal ratings, influenced the movement outcomes. Thus, we included only the data from the trials in which feedback was occluded with an IAPS image (i.e., each person completed 36 trials, Level-1: $n = 2,016$). Level-1 predictors included five continuous variables (code in parentheses): (1) SAM valence ratings (Val), (2) SAM arousal ratings (Ar), (3) Time (Time), (4) interaction between Time and Valence (Time \times Val) and (5) interaction between Time and Arousal (Time \times Ar). The predictor of time included three measurement points: 4, 8, and 12 s following image onset. Because the valence and arousal effects on movement may change as time progresses, we included the interactions between valence/arousal and time as predictors in the level 1 model. Level-2 predictors included three continuous variables: (1) level of depression (BDI), (2) level of trait anxiety (TA) and (3) subjects' MVC score (MVC). Depression is typically highly associated with trait anxiety. Therefore, we included trait anxiety as a level-2 predictor to isolate the effects of depression while controlling for trait anxiety. BDI scores were used to index subjects' level of depression, while STAI-T scores indexed level of trait anxiety. Both instruments showed high internal consistency (Chronbach's α : BDI = .88, STAI = .89). Additionally, subjects with higher MVC's display greater force decay and so to control for this effect, MVC was included as a level-2 predictor. The level-1 independent variables were group-mean centered and the level -2 independent variables were grand-mean centered.

Four HLM models at each target force level for each dependent variable were conducted. First, a random ANOVA (RA) model was run to test whether significant variation existed in the dependent variables between subjects. Second, a Mean as Outcomes model (MAO) was estimated to determine whether movement outcomes varied significantly as a function of depression once trait anxiety

and MVC had been controlled. Third, a random regression coefficient (RRC) model was conducted to test whether self reported measures of arousal or valence predicted between trial variations in movement outcome. Fourth, an intercepts and slopes as outcomes (IASO) model tested whether level of depression predicted person-specific level-1 (i.e., arousal, valence) effects. Restricted Maximum Likelihood was used to obtain estimates for the HLM analyses. Pseudo- R^2 values were calculated for the MAO, RRC, and IASO models. The Pseudo- R^2 values represent the portion of error variance in the model reduced by the introduction of the independent variables (Raudenbush and Bryk 2002). The following equations were used to calculate these values: (1) RRC model: $[\sigma^2(\text{RA}) - \sigma^2(\text{RRC})]/\sigma^2(\text{RA})$, where σ^2 represents the within person variance and (2) IASO model: $[\text{tau}(\text{RRC}) - \text{tau}(\text{IASO})]/\text{tau}(\text{RRC})$, where tau represents the between person variance of the level-1 slope. The level-1 and level-2 models for the IASO analyses were:

$$\begin{aligned} \text{Level 1: } CE_{ij} = & \pi_{0j}(\text{Intercept}) + \pi_{1j}(\text{Val}) + \pi_{2j}(\text{Ar}) \\ & + \pi_{3j}(\text{Time}) + \pi_{4j}(\text{Time} \times \text{Val}) \\ & + \pi_{5j}(\text{Time} \times \text{Ar}) + e_{ij} \end{aligned}$$

$$\begin{aligned} \text{Level 2: } \pi_{0j} = & \beta_{00} + \beta_{01}(\text{TA}) + \beta_{02}(\text{BDI}) + \beta_{03}(\text{MVC}) + r_{0j} \\ \pi_{1j} = & \beta_{10} + \beta_{11}(\text{TA}) + \beta_{12}(\text{BDI}) + \beta_{13}(\text{MVC}) + r_{1j} \\ \pi_{2j} = & \beta_{20} + \beta_{21}(\text{TA}) + \beta_{22}(\text{BDI}) + \beta_{23}(\text{MVC}) + r_{2j} \\ \pi_{3j} = & \beta_{30} + \beta_{31}(\text{TA}) + \beta_{32}(\text{BDI}) + \beta_{33}(\text{MVC}) + r_{3j} \\ \pi_{4j} = & \beta_{40} + \beta_{41}(\text{TA}) + \beta_{42}(\text{BDI}) + \beta_{43}(\text{MVC}) + r_{4j} \\ \pi_{5j} = & \beta_{50} + \beta_{51}(\text{TA}) + \beta_{52}(\text{BDI}) + \beta_{53}(\text{MVC}) + r_{5j} \end{aligned}$$

Constant error

The RA model indicated that significant variation existed among individuals in their performance (CE) on the pinch grip task at each target force level (See Table 2 for the estimates of the fixed and random effects for the RA models). The MAO model revealed that MVC significantly predicted the between-subject variation in CE at the 2 and 35% target force levels (Table 3 presents the estimates for the fixed and random effects for the MAO models). On the 2% of MVC trials, subjects with higher MVC's demonstrated greater CE (i.e., greater force production) on the pinch grip task (pseudo $R^2 = 7.6\%$). On the 35% of MVC trials, subjects with higher MVC's demonstrated greater force decay (Pseudo $R^2 = 17.4\%$).

Table 4 presents the fixed and random effects for the RRC models. The RRC model indicated that self-reported arousal had a significant positive relationship to CE within individuals at the 2 and 10% target force levels. As predicted, CE was greater (2%: above the target line; 10%: below target line) while viewing images rated as more arousing. At the 10% target level, valence also significantly predicted CE. Pictures rated relatively more pleasant compared to unpleasant led to greater CE. This result was likely driven by the higher arousal ratings given to the pleasant erotic pictures compared to all other pictures. Time was a significant predictor of CE at all three target force levels. As demonstrated in Fig. 3, CE increased as time progressed at the 2% target force level, whereas CE

Table 2 Fixed and random effects of the RA models for constant error (CE) and coefficient of variation (CV) at each target force level

	Fixed effect	Constant error			Coefficient of variation		
		Coefficient	SE	p value	Coefficient	SE	p value
2%							
	Intercept, π_{00}	0.0808	0.0188	0.001*	2.4873	0.1185	0.001*
10%							
	Intercept, π_{00}	-0.4036	0.0595	0.001*	1.8837	0.1038	0.001*
35%							
	Intercept, π_{00}	-4.3531	0.2586	0.001*	2.5396	0.1413	0.001*
	Random effect	SD	Variance	p value	SD	Variance	p value
2%							
	Intercept, u_{00}	0.1413	0.01996	<0.001*	0.8492	0.72107	<0.001*
	Level-1 effect, r_{ij}	0.1886	0.03556		1.9675	3.87119	
10%							
	Intercept, u_{00}	0.4497	0.20223	<0.001*	0.7133	0.50886	<0.001*
	Level-1 effect, r_{ij}	0.5056	0.25570		2.1395	4.57736	
35%							
	Intercept, u_{00}	1.9634	3.85495	<0.001*	1.0271	1.02706	<0.001*
	Level-1 effect, r_{ij}	1.8178	3.30435		2.1182	4.48657	

* = significant. Deviance for models conducted on CE: 2% = -860.60; 10% = 3275.13; 35% = 8637.31. Deviance for models conducted on CV: 2% = 8869.73; 10% = 9227.56; 35% = 9189.33. Number of parameters for all models = 2

Table 3 Fixed and random effects of the MAO models for constant error (CE) and coefficient of variation (CV) at each target force level

Fixed effect	Constant error			Coefficient of variation		
	Coefficient	SE	<i>p</i> value	Coefficient	SE	<i>p</i> value
2%						
For intercept slope, π_{00}						
Intercept, β_{00}	0.0808	0.0177	0.001*	2.4873	0.1167	0.001*
TA, β_{01}	0.0028	0.0024	0.247	0.0088	0.0153	0.567
BDI, β_{02}	0.0021	0.0035	0.547	0.0045	0.0129	0.729
MVC, β_{03}	0.0029	0.0012	0.022*	-0.0098	0.0089	0.277
10%						
For intercept slope, π_{00}						
Intercept, β_{00}	-0.4036	0.0584	0.001*	1.8837	0.1018	0.001*
TA, β_{01}	0.0055	0.0074	0.462	-0.0003	0.0130	0.982
BDI, β_{02}	-0.0028	0.0086	0.743	0.0195	0.0191	0.312
MVC, β_{03}	-0.0060	0.0046	0.203	-0.0067	0.0095	0.485
35%						
For intercept slope, π_{00}						
Intercept, β_{00}	-4.3531	0.2292	0.001*	2.5393	0.1376	0.001*
TA, β_{01}	-0.0123	0.0273	0.653	-0.0021	0.0161	0.896
BDI, β_{02}	-0.0340	0.0239	0.161	0.0289	0.0242	0.237
MVC, β_{03}	-0.0710	0.0164	0.001*	0.0132	0.0144	0.364
Random effect	SD	Variance	<i>p</i> value	SD	Variance	<i>p</i> value
2%						
Intercept, u_{00}	0.1362	0.01855	<0.001*	0.8608	0.74099	<0.001*
Level-1 effect, r_{ij}	0.1886	0.03556		1.9675	3.87119	
10%						
Intercept, u_{00}	0.4536	0.20570	<0.001*	0.7202	0.51873	<0.001*
Level-1 effect, r_{ij}	0.5056	0.25570		2.1395	4.57736	
35%						
Intercept, u_{00}	1.7841	3.18308	<0.001*	1.0270	1.05409	<0.001*
Level-1 effect, r_{ij}	1.8178	3.30435		2.1182	4.48657	

* = significant. Deviance for models conducted on CE: 2% = -843.38; 10% = 3299.10; 35; 35% = 8641.49. Deviance for models conducted on CV: 2% = 8889.95; 10% = 9215.37; 35; 35% = 9207.18. Number of parameters for all models = 2

decreased (force decayed) as time progressed without feedback at the 10 and 35% target force levels. The pseudo R^2 's at level-1 for the 2, 10, and 35% target levels were 20.9, 16.8, and 46.9%, respectively.

The level-1 slope significantly varied between subjects for the time-CE relationship at all target force levels and for the valence-CE and arousal-CE relationships at the 35% target force level. Therefore, to determine whether depression predicted the level-1 slopes we conducted an IASO model at each target force level, with Depression, Trait Anxiety, and MVC as the level-2 predictors (See Table 5 for the fixed and random effects of the IASO models conducted on the 2 and 35% of MVC trials). MVC significantly predicted the CE-Time slope at the 2% (pseudo $R^2 = 8.3\%$) and 35% target force levels (pseudo $R^2 = 30.8\%$). As revealed by the RRC model at the 2% target force level, CE increased across time following the removal of feedback. However, the magnitude of this relationship was stronger for those with higher MVC's.

Similarly, the level-1 relationship between CE and time at the 35% target force level was stronger for those with higher MVC's. In other words, individuals with higher MVC's exhibited more force decay across time than those with lower MVC's.

Also at the 35% target level, BDI scores significantly predicted the relationship between valence and CE (pseudo $R^2 = 4.5\%$). Subjects with BDI scores one standard deviation higher than the grand mean demonstrated a negative linear relationship between valence and CE, in which the more unpleasant the image, the closer the subject was to the target force (See Fig. 4). Thus, individuals higher in depression produced more force while viewing unpleasant rated images relative to pleasant rated images. Conversely, subjects with BDI scores one standard deviation below the grand mean demonstrated a positive linear relationship between valence and CE, in which the more pleasant the image the closer the subject was to the target. Thus, subjects lower in depression produced more force while

Table 4 Fixed and random effects of the RRC models for constant error (CE) and coefficient of variation (CV) at each target force level

Fixed effect	Constant error			Coefficient of variation		
	Coefficient	SE	<i>p</i> value	Coefficient	SE	<i>p</i> value
2%						
Valence, π_{10}	0.0030	0.0020	0.222	-0.1338	0.0518	0.013*
Arousal, π_{20}	0.0060	0.0020	0.011*	-0.0727	0.0544	0.187
Time, π_{30}	0.0110	0.0020	0.001*	-0.0193	0.0132	0.151
Time \times Val, π_{40}	0.0004	0.0002	0.108	0.0162	0.0064	0.015*
Time \times Ar, π_{50}	-0.0001	0.0004	0.667	0.0044	0.0056	0.442
10%						
Valence, π_{10}	-0.0145	0.0060	0.029*	0.0551	0.0384	0.152
Arousal, π_{20}	0.0183	0.0070	0.013*	-0.0484	0.0329	0.143
Time, π_{30}	-0.0281	0.0050	0.001*	-0.0224	0.0113	0.047*
Time \times Val, π_{40}	0.0005	0.0007	0.482	-0.0052	0.0035	0.137
Time \times Ar, π_{50}	0.0008	0.0008	0.365	0.0051	0.0038	0.180
35%						
Valence, π_{10}	0.0033	0.0270	0.905	-0.0169	0.0260	0.546
Arousal, π_{20}	0.0040	0.0261	0.880	-0.0757	0.0446	0.094
Time, π_{30}	-0.3312	0.0188	0.001*	0.0160	0.0161	0.327
Time \times Val, π_{40}	0.0011	0.0026	0.665	0.0026	0.0033	0.430
Time \times Ar, π_{50}	0.0007	0.0027	0.802	0.0010	0.0076	0.130
Random effect	SD	Variance	<i>p</i> value	SD	Variance	<i>p</i> value
2%						
Valence, u_{10}	0.0054	0.00003	>0.500	0.1213	0.01471	>0.500
Arousal, u_{20}	0.0100	0.00010	>0.500	0.2233	0.04990	>0.500
Time, u_{30}	0.0154	0.00024	0.001*	0.0232	0.00054	>0.500
Time \times Val, u_{40}	0.0021	0.00000	>0.500	0.0228	0.00052	>0.500
Time \times Ar, u_{50}	0.0011	0.00000	>0.500	0.0156	0.00025	>0.500
Level-1 effect, r_{ij}	0.1678	0.02814		1.9248	3.70470	
10%						
Valence, u_{10}	0.0168	0.00028	>0.500	0.1810	0.03227	>0.500
Arousal, u_{20}	0.0298	0.00089	>0.500	0.0894	0.00800	>0.500
Time, u_{30}	0.0326	0.00106	0.001*	0.0357	0.00127	>0.500
Time \times Val, u_{40}	0.0028	0.00001	>0.500	0.0147	0.00022	>0.500
Time \times Ar, u_{50}	0.0027	0.00001	>0.500	0.0133	0.00018	>0.500
Level-1 effect, r_{ij}	0.1678	0.02814		2.1213	4.50004	
35%						
Valence, u_{10}	0.0971	0.00944	0.001*	0.0510	0.00260	>0.500
Arousal, u_{20}	0.0961	0.00924	0.001*	0.2202	0.04850	>0.500
Time, u_{30}	0.1282	0.01644	0.001*	0.0845	0.00714	0.016
Time \times Val, u_{40}	0.0042	0.00002	>0.500	0.0119	0.00014	>0.500
Time \times Ar, u_{50}	0.0083	0.00007	>0.500	0.0459	0.00211	0.001
Level-1 effect, r_{ij}	1.3222	1.74812		2.0308	4.12425	

* = significant. Deviance for models conducted on CE: 2% = -1155.20; 10% = 3064.02; 35% = 8637.31. Deviance for models conducted on CV: 2% = 8855.54; 10% = 9227.56; 35; 35% = 9120.55. Number of parameters for all models = 22

viewing pleasantly rated images relative to unpleasant images.

Coefficient of variation

The RA model indicated that significant variation existed among individuals in their performance (CV) on the pinch

grip task at each target force level. (See Table 2 for estimates of fixed and random effects). However, the MAO model revealed that the between-subject variation in CV was not significantly predicted by the level-2 variables (See Table 3 for estimates of fixed and random effects of the MAO models). The RRC model conducted at 2% of MVC revealed that self-reported valence was significantly

Table 5 Fixed and random effects of the IASO models for constant error (CE) at the 2 and 35% target force levels

Fixed effect	2% of MVC			35% of MVC		
	Coefficient	SE	<i>p</i> value	Coefficient	SE	<i>p</i> value
For valence slope, π_{10}						
Intercept, β_{10}	0.0030	0.0023	0.207	0.0092	0.0256	0.721
TA, β_{11}	0.0001	0.0003	0.809	0.0020	0.0026	0.440
BDI, β_{12}	-0.0001	0.0003	0.685	-0.0092	0.0030	0.004*
MVC, β_{13}	0.0001	0.0002	0.987	-0.0007	0.0023	0.774
For arousal slope, π_{20}						
Intercept, β_{20}	0.0066	0.0024	0.009*	0.0059	0.0257	0.821
TA, β_{21}	0.0002	0.0003	0.528	0.0004	0.0029	0.876
BDI, β_{22}	-0.0001	0.0004	0.986	-0.0059	0.0045	0.200
MVC, β_{23}	-0.0003	0.0002	0.085	0.0024	0.0017	0.165
For time slope, π_{30}						
Intercept, β_{30}	0.0106	0.0021	0.001*	-0.3312	0.0159	0.001*
TA, β_{31}	0.0003	0.0003	0.338	0.0005	0.0019	0.777
BDI, β_{32}	0.0001	0.0004	0.872	-0.0034	0.0024	0.169
MVC, β_{33}	0.0004	0.0002	0.011*	-0.0060	0.0015	0.001*
For time \times valence slope, π_{40}						
Intercept, β_{40}	0.0002	0.0004	0.645	0.0002	0.0026	0.935
TA, β_{41}	-0.0001	0.0001	0.645	0.0001	0.0003	0.935
BDI, β_{42}	-0.0001	0.0001	0.866	0.0004	0.0005	0.402
MVC, β_{43}	0.0001	0.0001	0.570	0.0001	0.0002	0.629
For time \times arousal slope, π_{50}						
Intercept, β_{50}	0.0005	0.0003	0.081	0.0010	0.0025	0.697
TA, β_{51}	0.0001	0.0001	0.082	-0.0001	0.0003	0.676
BDI, β_{52}	0.0001	0.0001	0.849	0.0004	0.0003	0.134
MVC, β_{53}	0.0001	0.0001	0.342	-0.0001	0.0002	0.451
Random effect						
	SD	Variance	<i>p</i> value	SD	Variance	<i>p</i> value
Valence slope, u_{10}	0.0058	0.00003	>0.500	0.0949	0.00902	>0.500
Arousal slope, u_{20}	0.0101	0.00010	>0.500	0.0998	0.00997	>0.500
Time slope, u_{30}	0.0147	0.00022	0.001*	0.1067	0.01138	0.001*
Time \times valence slope, u_{40}	0.0022	0.00001	>0.500	0.0048	0.00002	>0.500
Time \times arousal slope, u_{50}	0.0010	0.00001	>0.500	0.0089	0.00008	>0.500
Level-1 effect, r_{ij}	0.1678	0.02817		1.3226	1.74944	

* = significant. Deviance for 2% model = -900.20. Deviance for 35% model = 7694.10. Number of parameters for all models = 22

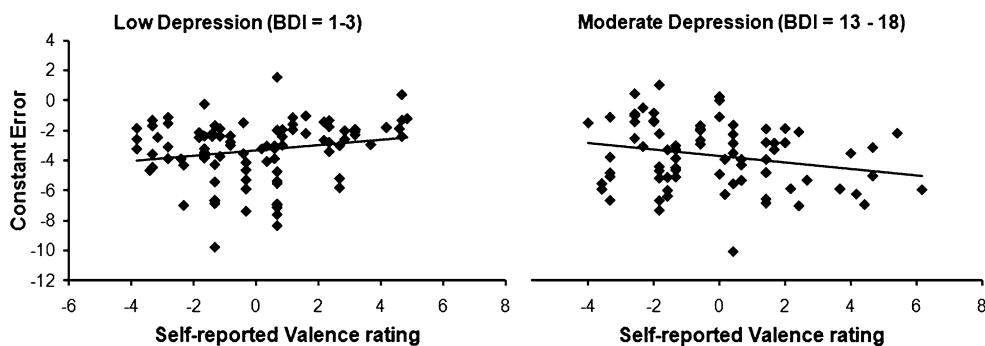


Fig. 4 The relationship between self-reported valence and CE as a function of BDI score at 12 s on 35% of MVC trials: *Left*—Subjects who reported an extremely low level of depressive symptoms (BDI

score between 1 and 3), *Right*—Subjects who reported moderate depressive symptoms (BDI score between 14 and 18). The self-reported valence ratings are group-mean centered

negatively related to CV within individuals (See Table 4 for estimates of fixed and random effects of the RRC models). Viewing images rated more unpleasant, relative to pleasant, resulted in greater CV. The time by valence interaction was also significant. The presence of such an interaction indicated that the magnitude of the valence effect depended on time. Our results indicate that the more unpleasantly rated pictures had a stronger impact on CV during the earlier portion of the trial. The pseudo R^2 was 4.3%, indicating that self reported valence and the time by valence interaction accounted for 4.3% of the variation in CV between trials at the 2% target force level. At 10% of MVC, time was significantly related to CV and accounted for 1.7% of the variation in CV between trials. Force production became less variable as the trial progressed. The level-1 variables did not significantly predict CV at the 35% target force level. The RRC models indicated that the relationship between the level-1 variables and CV varied only for the interaction terms at the 35% target force level. However, the IASO model conducted on the 35% of MVC trials revealed that none of the level-2 variables predicted this variation (Deviance = 9300.77, parameters = 22).

Discussion

We sought to determine whether (1) the impact of emotional state on force control varies as a function of target force level, (2) self reports of emotional state covary with force control, and (3) emotional state and trait levels of depression interact to alter force control. Subjects varying in level of depression (controlling for trait anxiety levels) sustained a pinch grip at a constant target force set at low, moderately low, and moderate target force levels. Visual feedback of performance was provided for the first 8 s and was then replaced with an emotional image for the final 12 s of each trial. The amplitude and variability of force production was analyzed using GLM and HLM models. Three novel contributions emerged. We determined that: (a) emotion driven changes in force control vary at different target force levels; (b) self-reported levels of arousal and valence covary systematically with the accuracy and variability of force control, and (c) individual differences in depression predict emotion driven changes in force control at moderate target force levels.

Emotional state, force control, and target force level

The first goal of the study was to assess whether arousal driven changes in force control are consistent across varying target force levels. Our findings demonstrated that emotional arousal leads to a relative increase in force production when target force levels are set at low and

moderately low target force levels, but not at moderate force levels. This finding replicates previous evidence showing that emotional arousal leads to a relative increase in force production at moderately low levels (Coombes et al. 2008), and extends this same finding to low target force levels.

The preliminary analysis conducted on the 2% of MVC trials revealed that the greatest decrease in force production occurred during exposure to neutral images. Exposure to the more arousing attack, mutilation, and erotica images, however, ameliorated force decay, resulting in a force trace closer to and above the target line. On the 10% of MVC trials greatest force decay was evidenced during the no feedback and neutral trials and least decay during the erotica and mutilation trials. The similarity in force output during exposure to pleasant and unpleasant stimuli converges with previous reports which have associated increases in emotional arousal with increases in corticospinal motor tract excitability (Coombes et al. 2009; Hajcak et al. 2007). As such, we interpreted the greater force production at low and moderately low target amplitudes under highly arousing conditions relative to neutral as reflecting a general pattern of heightened motor system excitability. Emotion did not influence force control at the 35% target force level. This null effect may have been driven by the moderating effect of depression on force tasks requiring greater exertion and increases in motor system activity.

The data further revealed that unpleasant rated images, relative to pleasant and neutral, increased variability (coefficient of variation) of force fluctuations only at the low target force level; an effect that was stronger during earlier picture presentation. This finding supports those of Christou (2005), who demonstrated that unpleasant emotional states (i.e., threat of shock), when coupled with feedback occlusion, lead to increased variability in force output on pinch grip tasks set to low target force levels. Our results also support Coombes et al. (2008), who found that affective images do not alter variability of force output at moderately low target force levels. In sum, these data suggest that the extent to which emotional state impacts the variability of force control is a function of the amplitude of the required target force. Our results combined with Christou's suggest that unpleasant emotional states may compromise motor control early in the onset of functional movements that require very low levels of force output when visual feedback is not available.

Our second aim was to determine whether self-reported levels of emotional arousal/valence correlate with motor output, and whether this relationship remains consistent at varying target force levels. Supporting our hypothesis, the HLM results showed that self-reported levels of arousal and valence predicted the accuracy and variability of

precision grip force control. Extending the extant behavioral and physiological data, our results demonstrate, for the first time, that changes in force control also covary with evaluative judgments of IAPS pictures. Hence, affective state prompts not only specific physiological responses, but also predictable changes in the control of functional motor tasks. This finding extends the scope of emotional reactivity and action readiness to overt motor performance (Frijda 2009; Frijda et al. 1989). Importantly, the observed affect driven motor responses were influenced by factors related to the task (i.e., target force level) as well as individual differences in dispositional levels of depression.

Subclinical depression and force control

The final objective of our study was to evaluate the influence of individual difference factors, particularly depression, on emotional reactivity as indexed by alterations in force production. Our data confirmed that individual differences in subclinical depression affected the relationship between emotional state and force control, and that this role is a function of target force level. The relationship between reported affective state and force control at moderate target force level (35%) varied according to individual differences in depression. Specifically, subjects reporting higher levels of depression displayed increases in force production while viewing images rated highly unpleasant relative to pleasant rated images. Conversely, subjects reporting lower levels of depression increased force production while viewing images rated highly pleasant relative to unpleasant rated images. These data suggest that depression modulates force control only when target force levels are at moderate levels.

The psychophysiological characteristics of emotional reactivity among depressed individuals have received considerable empirical attention. The extant data suggests that depression is characterized by reduced responsivity to pleasant emotional stimuli (Larson et al. 2007). Our results extended these psychophysiological findings by outlining a pattern of emotional responsivity as a function of depression within the functional motor system. Considering the present behavioral data and previous physiological evidence, we suggest that the amplitude of moderate force production provides an overt motor behavior correlate of depressed individuals' blunted response to pleasant emotional stimuli.

Two explanations likely underlie our collective findings and provide fruitful avenues for future work. First, it is logical to suggest that the *arousal response* was modulated by depression during exposure to pleasant and unpleasant images. Individuals reporting higher levels of depression likely experienced the typical highly arousing response to

the unpleasant images, but a diminished arousal response to the pleasant images. Additionally, individuals reporting extremely low levels of depression may have experienced a decreased arousal response to unpleasant rated images. In line with this argument, previous TMS work examining healthy controls has shown that exposure to highly arousing images compared to neutral images increases motor cortex excitability (Hajcak et al. 2007). Therefore, depressed individuals' diminished arousal response to pleasant rated images may have translated into decreased motor system excitability during exposure to pleasant compared to unpleasant rated images. We did not directly assess physiological indices of arousal in the present work and acknowledge this inferential limitation. Future research is necessary to provide physiological confirmation of the hypothesis that the arousal response to image content varies as a function of depression and covaries systematically with CE.

Secondly, performance differences on the pinch grip task due to depression could have been a function of the depth of processing of pleasant and unpleasant stimuli resulting from *altered attention* to them. Without the use of eye tracking, electroencephalography, or other inferential measures of attention, the current protocol cannot eliminate the possibility that differences in attentional allocation to disparate image content differentially interfered with the force production task. Individuals higher in depression may have displayed diminished attention to pleasant images relative to unpleasant images, resulting in reduced depth of processing of the pleasant stimuli. Gaze recordings during picture viewing would permit assessment of search strategies used when viewing pleasant and unpleasant images. Importantly, however, past research has shown that individuals with depressive disorders do not show differences in eye-tracking to affective stimuli (Mogg et al. 2000), providing support for our arousal-based interpretation of the results.

Contrary to our prediction, level of depression did not predict the relationship between self-reported affect and force production at low and moderately low target force levels. Our data indicate that at lower target force levels, replacing feedback with highly arousing pleasant and unpleasant images produces a sufficient arousal induced drive of the motor system to offset force decay in both healthy and individuals with subclinical depressive symptoms. Higher levels of force production (as in the moderate target force level trials) require greater activation of the motor cortex (Ehrsson et al. 2000). When 35% of MVC was required, depressed individuals' emotional responsivity to pleasant pictures may have been too low to increase force production at an observable behavioral level. Similarly, unpleasant pictures viewed by individuals extremely low in depression likely failed to produce an

increase in motor system activity sufficient enough to quantifiably alter force production at high target force levels. Loo et al.'s (2008) data corroborate this suggestion. They found that depressed individuals with psychomotor retardation exhibited a decreased ability to activate the motor cortex during an elbow extension task relative to a healthy comparison group. Importantly, this effect was greatest when the elbow extension task required maximal exertion. It is reasonable to speculate that individuals experiencing clinical levels of depression would likely exhibit an even more diminished emotional response to pleasant images than the individuals in the current study, who exhibited only subclinical levels of depression. As such, the pattern of results found at the moderate target force level might be present at lower target force levels in clinically depressed individuals, but this possibility remains to be empirically examined.

Finally, our HLM results may appear to be inconsistent with the literature showing that depression is associated with motor dysfunction (Caligiuri and Ellwanger 2000; Oathes and Ray 2006). Conflicting results are likely due to differences in subject population (MDD vs. subclinical levels of depression), differences in the movement parameters of interest (speed vs. force related parameters), and a lack of consideration for affective state. Researchers are encouraged to elucidate the degree of motor system dysfunction through which voluntary movements are executed in individuals with subclinical and clinical depression.

In conclusion, our findings provide seminal data to begin to delineate the interaction of subclinical dispositional depression and acute emotional contributions to alterations in sustained force production at three different target force levels. Emotional arousal reliably predicted alterations in force amplitude at low target force levels. Additionally, individual differences in subclinical depression interacted with emotional state to modulate force control when moderate levels of force production were required. These data permit strong inference that human motor control must adapt to moment to moment variations in affective state to yield effective motor performance, and that such variations differ as a function of individual differences in subclinical depression. A comprehensive understanding of how task characteristics interact with state and trait emotions to influence motor behavior may help clinicians to create more objective means to identify psychomotor impairments in depression. Given the known behavioral and neurobiological integration of the emotion and motor systems, learning how to use the motor system to drive affective changes could be a fruitful avenue for future research as well as an empirically founded conduit through which clinicians can appropriately assess and treat affective disorders.

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