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Enhanced performance on executive functions associated with examination stress: Evidence from task-switching and Stroop paradigms

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Stressful life situations can impair or facilitate various cognitive functions. In the present study, the effect of examination stress on students was examined using two executive function tasks, task-switching and the Stroop task, in a between-subject crossover design. Students showed increased anxiety in the 2 week period prior to exams compared to the beginning of the semester, manifested as higher scores on the Spielberger State-Trait Anxiety Scale and a shift to more sympathetic activation when heart rate variability was assessed. During the stressful period, the switching cost was reduced on a spatial task-switching paradigm and reaction times in the Stroop task were faster. This is the first study to show stress-induced facilitation of performance on these executive function tasks.

The impact of stress on high order cognitive functions is of prime practical and clinical importance. Both facilitatory and detrimental effects of stress on memory have been reported, but there is a dearth of experimentation on the effect of stress on other higher cognitive functions. Cognitive function may be affected by common stressors experienced by the patient (marital strife, illness of a family member, work problems), or the testing situation itself. Although it is generally assumed that stress impairs cognitive functioning, the present study, showing facilitatory effects of examination stress on executive functions, suggests that moderate stress can be beneficial in healthy participants.

The notion that stressful events can have both facilitatory and detrimental effects on performance of cognitive or perceptual tasks is viewed as an extension of the inverted U or Yerkes-Dodson Law (Yerkes & Dodson, 1908), which suggests that performance of a given task deteriorates if arousal levels are below or

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above an optimal level. Although Yerkes and Dodson (1908) actually examined the effect of different levels of punishment on discrimination learning in mice, psychologists subsequently applied their principle to human studies on the interaction of arousal and performance. Arousal has been manipulated either by testing at different times of day, administering drugs such as caffeine, or has been considered an inherent subject characteristic based on a personality inventory. For instance, introverts or people scoring low on an impulsivity scale are considered to have high arousal levels, whereas extroverts or those with high impulsivity are purported to have low arousal (Revelle, Humphreys, Simon & Gilliland, 1980; Watters, Martin, & Schreter, 1997). Both high and low doses of caffeine impeded performance, with respect to intermediate doses, on a task that involved serial enumeration of letters and numbers (Watters et al., 1997). Caffeine was also found to interact with time of day and impulsivity, such that it ameliorated performance under conditions of low arousal, but impaired performance under conditions of high arousal (Revelle et al., 1980). However, physiological evidence suggests that ‘‘arousal’’ can no longer be considered to be a unitary entity, as it is affected by numerous parallel neuronal and hormonal pathways and has several physiological and psychological manifestations which are not always correlated (Mendl, 1999). For the present study, we used a natural situation, examination stress, rather than drug- or stimulus-induced manipulations of arousal. Stress and arousal, although not interchangeable concepts, have similar effects on learning and cognitive performance (Sanders, 1983), such that the distinction for the present study is moot. Stress was defined operationally by a self-report questionnaire and changes in heart rate variability, rather than by measures of general alertness or arousal. Numerous studies have used hormones that mimic the physiological stress response in order to study the effects of stress on different cognitive processes, just as caffeine is used to induce changes in arousal. Hydrocortisone, an analogue of the human adrenal stress hormone, cortisol, reduced reaction times in a recognition memory task in the late afternoon, when endogenous cortisol levels were at their trough (Lupien, Wilkinson, Brière, Ménard, Ng Ying Kin, & Nair, 2002), whereas in other studies analogues of cortisol impaired free recall or recognition of verbal material in healthy volunteers (de Quervain et al., 2000, 2003; Newcomer et al., 1994, 1999; Young, Sakhanian, Robbins, & Cowen, 1999; Wolkowitz et al., 1990) or in patients with Cushing’s syndrome, who overproduce corticosteroids (Starkman et al., 1999). These studies and others (reviewed by Mendl, 1999; Sanders, 1983) suggest that the effect of stress on performance might be best depicted by an inverted U-function, facilitating performance when endogenous levels of the stress hormone are low, and impairing performance if endogenous levels are high. However, it should be noted, that this interpretation is limited, as most of the studies cited did not monitor cortisol levels, stress, or arousal before administering the drug to volunteers.

The suggestion that the effect of stress on learning and memory is best described by an inverted U-function is supported by studies in infrahuman species. Both high and low levels of a drug mimicking the rodent adrenal stress hormone, corticosterone, impeded long-term potentiation (LTP), a physiological model of hippocampal learning in rats, whereas moderate doses facilitated LTP (Diamond, Bennett, Fleshner, & Rose, 1992; Kim & Diamond, 2002). Similarly, working memory in monkeys was facilitated by moderate stress or moderate dopamine stimulation, but was impaired if either stress or prefrontal cortical dopamine stimulation was above or below the optimal level (Arnsten, Cai, Murphy, & Goldman-Rakic, 1994).

At first glance, the fact that both detrimental and facilitatory effects of stress on cognition have been reported obfuscates any hypothesis that could be formulated on this topic. Although this presents a challenge to the field and fosters a tendency to emphasise stress-induced deficits in performance, the current study is based on the premise that in a healthy population, stress can facilitate tasks that require selective inhibition of prepotent responses.

Examination stress in university students has been used as a naturalistic paradigm for the investigation of both physiological and cognitive consequences of stress in healthy participants (Malarkey, Pearl, Demers, Kiecolt-Glaser, & Glaser, 1995; Lucini, Norbiato, Clerici, & Pagani, 2002). Vedhara, Hyde, Gilchrist, Tytherleigh, and Plummer (2000) reported enhanced performance on a memory task following examination stress, despite deterioration in two attention tasks. The involvement of the prefrontal cortex (PFC) in stress-cognition interactions is suggested by working memory deficits in humans (Wolf, Schommer, Hellhammer, McEwen, & Kirschbaum, 2001; Young et al., 1999) and infrahuman primates (Arnsten et al., 1994) following administration of analogues of the adrenal stress hormone and by anatomical evidence that the PFC has an abundance of receptors for this hormone that are activated by the high levels that are attained during stress, but not by the hormone levels that are attained in routine activities (Lupien & LePage, 2001). Despite the evidence in favour of PFC involvement, surprisingly few studies have examined the effects of stress on executive functions, such as inhibition of prepotent responses, response selection, and monitoring. Specific regions, such as the anterior cingulate cortex, middle and inferior frontal gyrus, are critical for regulation of the autonomic nervous system during performance of the Stroop task (Matthews, Paulus, Simmons, Nelesen, & Dimsdale, 2004) as well as for regulating the inhibitory component of stop and switching (Garavan, Ross, Li & Stein, 2000; Garavan, Ross, & Stein, 1999). In the present study, the effect of examination stress on two executive function tasks, task-switching and Stroop colour naming was studied. The choice of the Stroop and task-switching paradigms was based on the hypothesis that, because regulation of the stress response (Diorio, Viau, & Meaney, 1993; Jackson & Moghaddam, 2001) and inhibition of prepotent responses activate some common PFC regions, in particular the anterior cingulate cortex (Duncan & Owen, 2000; Garavan, Ross, Murphy, Roche, & Stein, 2002), stress in a healthy population would enhance performance on these tasks.

The Stroop color naming task is believed to tap executive functions because participants are required to act in opposition to their habitual tendencies (i.e., to name the ink colour of the word instead of reading the word). Overcoming this habitual tendency is accompanied by a slowing of the response time (for a review, see MacLeod, 1991). Brain imaging studies indicate that overcoming the habitual response tendency activates the anterior cingulate gyrus (Carter et al., 1998; Swick & Jovanovic, 2002) and the dorsolateral PFC (MacDonald, Cohen, Stenger, & Carter, 2000) as well as parietal regions.

The task-switching paradigm requires subjects to rapidly switch between two tasks performed on the same set of stimuli (such as switching between colour naming and word reading (e.g., MacDonald et al., 2000). The task-switching requirement also activates the dorsolateral and lateral PFC (Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000; Dreher & Berman, 2002; MacDonald et al., 2000; Sohn, Ursu, Anderson, Stenger, & Carter, 2000) and the pre-supplementary motor area/anterior cingulate cortex (e.g., Dreher & Berman, 2002; MacDonald et al., 2000). This is also true for the paradigm we used in the present study (Brass et al., 2003). In the spatial task-switching task used in the current study, the participants were required to respond to the location of a target stimulus (smiling face character) in a 2 × 2 matrix as being either on the left or right (Task A) or up or down (task B). Each trial began with a task cue, indicating which one of these two tasks was required. When the participant is required to switch from Task A to Task B (AB), the reaction time (RT) is slower than the RT obtained when the task is repeated (e.g., AA). This decrement in RT is known as the task-switching cost. Varying the cue-target interval (CTI) allows a measure of the preparatory component of the switching cost. Switching cost is reduced in long, compared to short CTIs (Meiran, Chorev, & Sapir, 2000).

Moreover, when the performance on blocks of mixed trials (A or B in random order), in which switching can occur, is compared to that of performance on blocks of single task trials (AAA or BBB), where there is no possibility of switching, the RT on the former task is slower. This is known as mixing cost. Thus, the decrement in RT observed between a trial from a single task block and a switch trial within a mixed list block is called the alternation cost, which is comprised of the switching cost (switch minus no-switch) and the mixing cost (no-switch in mixed list minus single). Previous work has shown that the switching cost can be reduced by presenting an unrelated arousing cue before the task cue (Meiran & Chorev, 2005; cf. De Jong, Berendsen, & Cools, 1999). Switching cost and task-mixing cost have shown to be dissociable. For example, elevated switching cost and relatively normal mixing cost is found in several populations, such as children with attention deficit hyperactivity disorder (Capeda, Capeda, & Kramer, 2000). The reverse pattern, namely elevated mixing cost and less elevated switching cost, is found among normal elderly participants (Kray & Lindenberger, 2000; Meiran, Gotler, & Perlman, 2001). Elevated switching cost is also found in patients with left frontal lesions (Rogers et al., 1998). A recent functional magnetic resonance imaging (fMRI) experiment showed that the transient switching cost activated predominantly left dorsolateral and ventrolateral PFC and superior parietal cortex, whereas the more sustained mixing cost activated right hemisphere medial, lateral, and anterior frontal cortex (Braver, Reynolds, & Donaldson, 2003).

In order to measure the effect of examination stress on the participants, we administered a self-report questionnaire, the Spielberger State-Trait Anxiety Inventory (STAI) and measured baseline heart rate variability at each session. Increased heart rate variability (HRV) is often used as a measure of vagal tone in patients with stress disorders. This can be measured as the mean R-R interval, or if the R-R intervals are analysed by Fourier transformation, the high frequency range (HF, 0.15–0.40 Hz) is attributed to parasympathetic activity and the low frequency (LF, 0.04–0.15 Hz) range is attributed to both sympathetic and parasympathetic activity (Task Force, 1996). Increased sympathetic tone (measured as decreased R-R interval) was associated with higher salivary cortisol, more eye contact, and a lower incidence of escape behaviours following social stress in humans (Sgoifo et al., 2003) and greater Stroop interference and longer RTs to name colours of dentist-related words in subjects with odontophobia (Johnsen et al., 2003). Similarly, greater R-R variability (greater parasympathetic activity) after aerobic training was associated with improved and faster performance on working memory and continuous performance tests (CPT) with an executive function component (Hansen, Johnsen, Sollers, Stenvik, & Thayer, 2004). These studies underscore the relationship between autonomic control and cognitive performance, and suggest that performance on tests of attention and working memory is better in individuals with more vagal tone.

We hypothesised that participants would have higher scores on the state anxiety inventory and a higher ratio of low/high frequency activity on the spectral analysis of the HRV during the period preceding examinations (stress) compared to the beginning of the semester (no stress). We further predicted that stress would reduce the switching, but not mixing cost in the task-switching paradigm, and would reduce the Stroop interference (difference between incongruent and congruent reaction times).

METHOD

Participants

A total of 48 freshman undergraduates (7 males), aged 19–29 (mean + *SD* 22.4 ± 1.52) from the Department of Behavioral Sciences at Ben-Gurion University were recruited for the study in exchange for points in an introduction to psychology course. Since the acceptance to graduate school in psychology is extremely competitive and it is based, in part, on undergraduate grades, the examination periods are perceived by students in the Department of Behavioral Sciences to be very stressful. The students were assessed for stress and tested at two intervals, at the beginning of the semester and 2 weeks prior to the first semester examinations. All participants were administered a short questionnaire to rule out history of traumatic head injury that involved loss of consciousness or neurological or psychiatric disorders requiring medication.

Design

Because some of the tasks being used showed marked practice effects in previous studies (e.g., Meiran et al., 2000, concerning the task-switching paradigm) the present study was designed as a between-participant study. However, between-participant studies suffer from shortcomings, such as self-selection bias (i.e., participants who would choose to participate in the study a short time before the examination period would be different from those who would volunteer in the mid semester). In order to overcome these shortcomings, the design was similar to that of within-participant studies in the sense that all participants were recruited in advance and were tested both in the mid semester and shortly before the examination period. However, each participant was tested on a different set of executive function tests in each testing period. Therefore, each participant served in the control condition for one function and in the experimental condition in the other function. This was possible due to the fact that, although practice within a given executive functions test affects performance, there is virtually no effect of transfer-of-training between different executive function tests, even between those that measure correlated functions. For example, there are significant unique correlations between two task-switching paradigms, one involving object tasks (shape, size) and the one involving location tasks (Yehena & Meiran, 2006) but training in the spatial paradigm does not transfer to the object paradigm (Armoni-Shimoni, 2001; Sosna, 2001).

Assessment of stress levels

Two measures were used to assess stress at both time points: an anxiety questionnaire, as a subjective measure, and heart rate variability as a physiological measure modified by both the sympathetic and parasympathetic autonomic nervous systems. The Hebrew version (by Teichman & Melnick, Ramot, Tel-Aviv University, 1984) of the Spielberger State-Trait Anxiety Scales (Spielberger, 1975) was used as a subjective measure of state and trait anxiety. The Trait Anxiety Scale was administered only in the first session (beginning of semester) and the State Anxiety Scale was administered at both time points.

Heart rate variability

Heart rate variability (HRV) was measured at both time points while the participants were seated, using a Holter Monitor (Oxford 4-24) to measure ECG with wrist and ankle clamp electrodes. The ECG was measured for 10 minutes, while the participants were sitting in a relaxed state, and stored on tape. ECG data were amplified and digitised at a rate of 500 Hz, filtered by a band pass of 0.05–35 Hz. The ECG signal was converted into an event series, which required the measurement of R-R intervals, using the method described by Cohen et al. (2000). Power spectrum analysis (PSA) of HRV, calculated as ms^2/Hz was done using Fast-Fourier Transform using signal-processing software (BEAT; Ben-Gurion University). The QRS complex was visually inspected and irregular beats, electrical artifacts, and premature ventricular beats were rejected, together with the interval preceding and following the event. The spectral power was expressed as $ln \times ms^2/Hz$, where *ln* is the natural logarithm of the quotient after measurement of the areas of the two frequency ranges: low frequency (LF, 0.04–0.15 Hz) and high frequency (HF, 0.15–0.40 Hz).

The following measures were derived from the PSA: HF, LF, ratio of LF/HF, percentage HF and percent LF. The best indication of a change in sympathetic activity is considered the LF/HF ratio, as HF is known to reflect parasympathetic activity and to be sensitive to cholinergic drugs (Task Force, 1996). On the other hand, the contribution of sympathetic activity to LF is more ambiguous, as both sympatomimetic and parasympatomimetic drugs affect LF activity (Task Force, 1996).

Task switching

A spatial task-switching paradigm (Meiran et al., 2001, experiment 1) was programmed in MEL language (Schneider, 1988) and the stimuli presented in white on black using graphic symbols in the extended ASCII code, on a 14 inch computer monitor (IBM clone). This paradigm requires judging the position of a target stimulus according to either one of two task rules: UP-DOWN and RIGHT-LEFT, with the relevant rule cued in the beginning of each trial. Stimuli were presented in a 2×2 cm grid in the center of the monitor. A Smiley (width subtending 3° and height 5° from the subject) in one of the 4 squares served as the target. The task cues consisted of arrowheads $3^\circ \times 3^\circ$, placed 7° from the edge of the grid. The arrows for the RIGHT-LEFT task consisted of a right pointing arrow to the right of the fixation point and a left-pointing arrow to the left of the fixation point. The arrows for the UP-DOWN task were above and below the fixation point. The fixation point was a ‘‘+’’ sign subtending a visual angle of approximately 3° (width) $\times$ 5° (height). The participants responded on the number pad of the computer keyboard. For half the participants, keys 1 and 9 represented down and left and up and right, respectively, and for the other half, keys 3 and 7 represented down and right and up and left, respectively. The up-down task was used in the single task block for half the participants and the left-right task was used for the other half. For each participant half the trials had a congruent response. For example, when the target appeared in the upper left corner, the response key 7 was correct with respect to both up and left cues, but when the target appeared in the lower left corner of the grid, 7 was the correct choice in the left-right task, but nonetheless spatially incongruent with respect to its up-down position.

Testing on the task-switching paradigm consisted of a training block followed by four 80-trial experimental mixed blocks and one 80-trial block of single task trials. Each trial included: (1) presentation of a blank grid during the fixed response-cue 2016 ms; (2) presentation of the arrow cues during the cue-target interval (CTI, 116 or 1016 ms, varied pseudo-randomly within a block; (3) presentation of the target which lasted until the participant's keyboard response. The participant was asked to respond to the relevant task, as defined by the arrow cues, by hitting the appropriate key (right-left or up-down) as stated above. Thus, the design consisted of the following independent variables: CTI 116 or 1016), task transition (switch, no-switch, or single task), congruency (congruent or incongruent), and the stress manipulation (beginning of semester or examination period). The dependent variable was reaction time (RT) to respond. Aberrant response times (100 ms<RT<3000 ms, less than 1% of all responses) were omitted from the analysis.

Stroop colour naming

This task requires naming the ink colour in which colour words are written, with the ink colour being either congruent or incongruent with respect to the colour word (e.g., the word RED printed in red ink or in green ink, representing a congruent and an incongruent condition, respectively). A white asterisk appeared in the middle of the screen for 500 ms, followed by the stimulus word after an interval of 500 ms. The participant was instructed to vocally name the colour as quickly as possible and reaction time (RT) was measured using a microphone and a voice key. The four stimulus words were the Hebrew equivalents of blue, green, yellow, and red (each 4 letters and 2 syllables) and the neutral stimulus was a 4 letter string of the letter ''shin'', which does not appear in any of the words (Tzelgov, Henik, & Berger, 1992). Each of these five stimuli was presented in each of the 4 colours. Presentation of the stimuli was balanced such that each colour name appeared 12 times and the neutral stimulus appeared 24 times for a total of 72 stimuli. The RT to name congruent stimuli (word matching the colour) was compared to the RT to name incongruent stimuli (word differing from colour) and to the RT to name the colour of the neutral stimulus. Aberrant response times (100 ms<RT<3000 ms, less than 1% of all responses) were omitted from the analysis.

Procedure

In the first session, all participants were first administered a screening questionnaire (see above), followed by a 10 minute session of ECG recording. During this time the participant sat quietly and was not engaged in any of the experimental tasks. Following this, participants were given the Spielberger State-Trait Anxiety questionnaires. Half the participants then performed either task-switching or Stroop colour naming in the first session and half performed task switching or Stroop in the second session. The order of task administration was counterbalanced across the participants. All participants were tested during the daytime (8 am–6 pm).

During the second session, the procedure was similar except that the participants did not complete the Trait Anxiety questionnaire. Each participant then performed the task that they did not carry out in the first session. In addition, in the second session a 10-item ''anxiety-enhancing'' questionnaire was orally administered between the training block and the onset of the task. The questionnaire related to study habits, attendance in classes, and confidence in scholastic success (e.g., How many hours a day to you devote to studying? How do you rate your chances of being accepted to graduate school?).

RESULTS

State-Trait Anxiety questionnaire

Data were analysed for 47 participants who completed both phases of the experiment. A paired one-tailed t-test was used because of an a priori assumption that anxiety scores would be higher during the examination period. As predicted, the total State Anxiety score was higher (Mean $\pm$ *SD* = 33.3 $\pm$9.37) during the second phase of the experiment than at the beginning of the semester (31.2$\pm$7.53), $t(46) = 1.88$, $p < .05$.

Heart rate variability

Dependent one-tailed *t*-tests were conducted on the data from 30 participants whose data were available at both time points. The one-tailed test was chosen because of our a priori hypothesis that there would be increased sympathetic low frequency (LF) activity during the exam period. The other data were rejected due to technical failure. A significant difference was found in the percentage of LF, $t(29) = 3.14$, $p < .002$, and the percentage of high frequency (HF), $t(29) = 3.14$, $p < .002$, such that the percentage of LF increased in the period preceding examinations while the percentage of HF decreased (Table 1).

High frequency (HF) is related to vagal parasympathetic tone, whereas low frequency (LF) is related to both parasympathetic and sympathetic activity. In order to determine if there was an increase in sympathetic tone, the LF/HF ratio was analysed, as described in Cohen et al. (2000). However, the effect on the LF/HF ratio fell just short of significance by a one-sided test, $t(29) = 1.67$, *ns*. These results indicate a moderate increase in sympathetic activity and a concomitant decrease in parasympathetic activity during the examination period.

TABLE 1
Percentage of low frequency (LF) and high frequency (HF) heart rate variability (HRV) spectrum during the two phases of the experiment, mean (SD) (N = 30)

Percentage of HRV	*Beginning of semester*	*End of semester*
LF (%)	49.2 (17.5)	59.7 (16.5)
HF (%)	50.8 (17.5)	40.3 (16.5)

Task-switching

Based on the fractionation of switching cost and mixing cost (Capeda et al., 2002; Fagot, 1994; Kray & Lindenberger, 2000; Los, 1999; Meiran et al., 2000) two separate analyses were conducted. In one analysis, we compared switch and no-switch trials to test effects related to switching cost. The second analysis compared no-switch trials to single task trials to examine mixing cost. Additional independent variables were testing period (beginning of semester/period preceding exams), CTI (116 ms or 1016 ms), task transition (single task/ no switch/ switch), response repetition (repeat/ switch) and congruence (congruent/ incongruent) in a 5 way ANOVA with CTI, task-transition, switch, and response repetition as repeated measures. Analysis of switching cost (switch minus no-switch) revealed that the switching cost in participants who performed the task at the beginning of the semester was 97 ms, compared to 63 ms in participants who performed the task prior to examinations, $F(1, 46) = 4.74$, $p < .05$. This effect was not involved in any further interactions. In addition, the usual interactions between the other variables were obtained (e.g., CTI × Switch, Switch × Response-Repetition, see Meiran et al., 2001). In contrast, the stress during the examination period did not significantly affect mixing cost (defined as the difference between single task blocks and mixed task blocks), $F(1, 46) < 1$, $MSE = 42950.9$. (See Figure 1.)

In an effort to better understand this effect of stress on the cost of task-switching, we performed a procedure known as Vincentizing (Ratcliff, 1979). Instead of analysing the mean of each condition, we represented each condition by five different RT percentiles: the 5th, 25th, 50th, 75th, and 95th, which allowed us to determine the part of the RT distribution that was most affected by stress. We found a significant triple interaction between the switch contrast, stress, and percentile, $F(8, 368) = 2.50$, $p < .05$. Examination of the means (Figure 2) revealed that stress facilitated the very slowest switch RTs in the 95th percentile and did not affect the rest of the distribution. The switch cost for the RTs in the 95th percentile was significantly lower in the stress period than at the beginning of the semester $F(1, 46) = 8.36$, $MSE = 147668$, $p < .01$. (Due to the disproportionate number of women, we compared the effect size of the stress ×

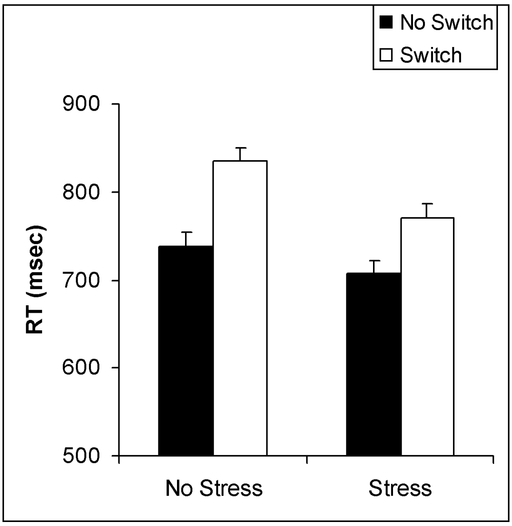


Figure 1. Reaction time (ms) for switch and no-switch trials in task-shifting task. Participants were tested at the beginning of the semester (no stress, $N = 25$) and 2 weeks before exams (stress, $N = 23$). The interaction between stress and task was significant, $F(1, 46) = 4.74$, $p < .05$.

switch cost interaction for the entire population using partial eta-squared for the women alone and the entire sample; $\eta^2 = .09$ for the entire sample and .06 for the women alone, suggesting that the effect is similar in both cases).

The proportion of errors (PE) was very low, with an average of .019 overall and 0 in more than half of the 24 cells. Therefore, the PE data were not analysed using ANOVA, but rather were examined qualitatively. This examination indicated that there was no evidence for speed-accuracy trade-off.

Stroop colour naming

A 2-way ANOVA was carried out for the effect of test period (beginning of semester or examination period) and congruency. The RT during the examination period was significantly shorter (652 ± 87 ms) $F(1, 46) = 5.69$, $MSE = 30510$, $p < .05$ than at the start of the semester (721 + 114 ms). In addition, a main effect for congruency was found, as expected, $F(2, 92) = 98.59$, $MSE = 2061$, $p < .01$. Further analysis revealed a typical inhibitory effect of incongruent stimuli, such that RTs for incongruent stimuli (759 + 128 ms) were slower than for congruent (648 + 110 ms) or neutral stimuli (646 + 96 ms). There was no significant difference between congruent and neutral stimuli $F(1, 46) = .07$, $MSE = 1337$, ns, and no significant interaction between the test period and congruency $F(2, 92) = .08$, $MSE = 2061$, ns (Figure 3). (The effect size for the

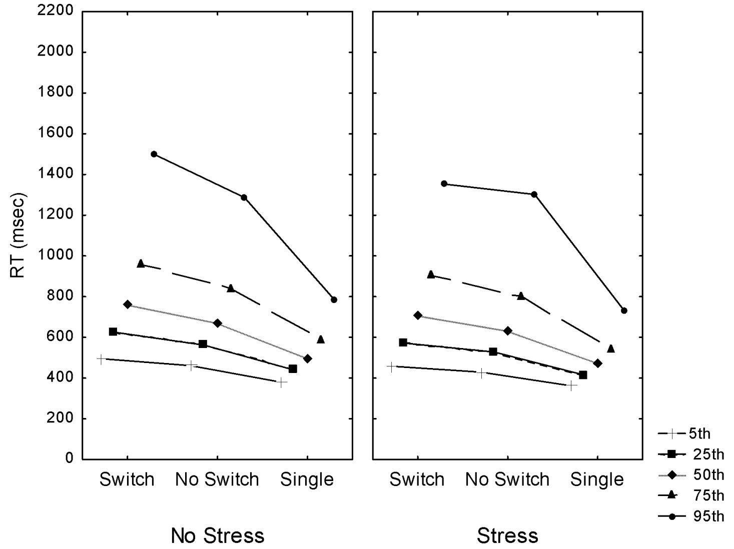
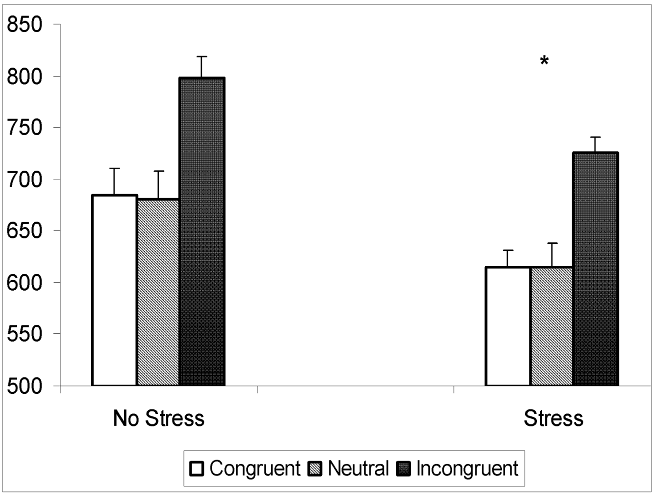


Figure 2. Vincentized analysis of the distribution of reaction times (RTs) for switch, no-switch, and single task conditions at the beginning of the semester and two weeks before exams (stress). The symbols represent the distribution of the RTs in the 5th, 25th, 50th, 75th, and 95th percentiles. The interaction between stress, task, and percentile indicated that the switch cost for the RTs in the 95th percentile was smaller during the Stress period than the No Stress period.

entire sample was $\eta^2 = .11$ and for the women alone .16, suggesting that the RT reduction was similar in both cases.)

In order to determine if stress preferentially reduced the longest RTs, we performed the Vincentizing procedure, as described above. Although this analysis revealed a significant interaction between percentile and stress, $F(4, 184) = 4.38$, $MSE = 8529$, $p < .01$, planned comparisons between the stress and non-stressed group for each percentile revealed that the RTs were faster during the examination period for each or the 95th $F(1, 46) = 8.37$, $MSE = 7429$, $p < .01$, 75th $F(1, 46) = 5.07$, $MSE = 35722$, $p < .05$; 50th percentile $F(1, 46) = 4.08$, $MSE = 30052$, $p < .05$, 25th $F(1, 46) = 4.84$, $MSE = 24910$, $p < .05$ and 5th $F(1, 46) = 4.64$, $MSE = 23924$, $p < .05$ percentiles (inset Figure 3). There were no significant interactions between the stress variable and congruency, suggesting that the Stroop interference was not affected by the examination stress.

The percent of errors was very low, and did not differ between sessions, $F(1, 46) = .06$, $MSE = .00048$, n.s. As expected, there were more errors for the incongruent stimuli (.02% + .01), than for the congruent (.005% + .01) and neutral stimuli (.004% + .001), $F(2, 92) = 14.37$, $MSE = .0004$, $p < .01$. There was no interaction between the session and congruency, $F(2, 92) = .38$, $MSE =$



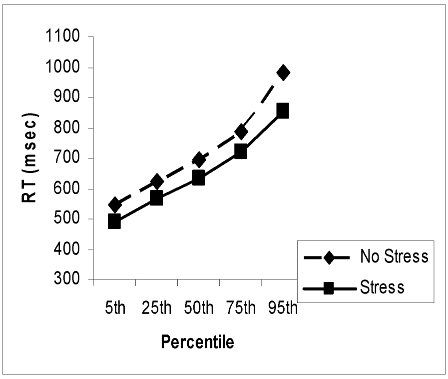


Figure 3. Top panel, RT's for Stroop color naming at the beginning of the semester (No Stress) and before examinations (Stress). Main effect of test period and for congruency (see text). (Bottom panel), Vincentized analysis of RT data, showing the interaction between percentile and stress. The RTs during the Stress session were faster than the RTs in the No Stress session at each time point.

.0004, n.s., suggesting that the improvement in RT in the second session was not at the expense of increased errors.

DISCUSSION

This study is the first to demonstrate facilitatory effects of stress on two executive function tasks, specifically: (1) reduced switching cost in a spatial switching task; and (2) a reduction in reaction time (RT) in the Stroop paradigm, with no change in the Stroop interference. The analysis of the task-switching data indicates that the reduction in switch cost was due primarily to reduction in the number of long RTs during the stressful period, with no effect on intermediate and short RTs. On the other hand, the reduction RTs for the Stroop paradigm was significant throughout the distribution, although the significant interaction between percentile and stress suggest that the longer RTs were reduced more by stress.

The principal components analysis outlined by Miyake, Friedman, Emerson, Witzki, & Howerter (2000) suggests that the Stroop task is dependent to a large degree on inhibitory processes, whereas task-switching is more strongly represented by a shifting process. However, task-switching involves inhibition of a previously active task, such that performance on this task correlates with performance on other tasks of inhibition of prepotent responses (Friedman & Miyake, 2004). Performing a given task primes the tendency to perform it again on the following trial. If that trial requires a task switch, successful performance depends on one's ability to overcome this perseverative tendency (Allport & Wylie, 2000; Mayr & Keele, 2000; Meiran & Daichman, 2005). An alternate interpretation derived from the model of De Jong et al. (1999) on the switching cost is that stress facilitated the exploitation of executive processes, or in their terms, reduced ''goal neglect''.

The profile derived from the subjective, physiological, and cognitive stress measures suggests a nonpathological, and perhaps adaptive elevation in stress during examination. The enhancement of stress during the examination period was supported by two independent measures: the significantly higher scores on the Spielberger State Anxiety questionnaire and an increase in the percentage low frequencies (LF) and a decrease in vagal regulation of heart rate variability (HRV), percentage high frequency (HF). The State Anxiety scores did not reach the pathological values typical of patients suffering from depression (Osuch et al., 2000) and were typical of scores during examination stress (MacLeod & Rutherford, 1992). The use of HRV as a physiological measure of stress is validated by previous studies which showed that parasympathetic activity has been negatively correlated with behavioural and self-report measures of stress (Sgoifo et al., 2003) and with salivary cortisol (Lucini et al., 2002; Sgoifo et al., 2003).

Stress was also shown to enhance performance on spatial tasks in rodents (Bowman, Zrull, & Luine, 2001) and tree shrews (Bartolomucci, de Biurrun, Czéh, van Kampen, & Fuchs, 2002). The present study can be compared to studies that used exogenous analogues of cortisol to induce a physiological stress-like state or to studies in which learning of emotional stimuli (inducing the stress response) were compared to neutral stimuli. Exogenous cortisol facilitated acquisition of verbal or pictorial stimuli (Abercombie, Kalin, Thurow, Rosenkranz, & Davidson, 2003; Buchanan & Lovallo 2001; Tops et al., 2003) and reduced reaction time in a spatial task in healthy volunteers (Young et al., 1999). Emotionally arousing stimuli were remembered better in explicit (Canli, Zhao, Brewer, Gabrieli, & Cahill, 2000) and implicit (Gidron, Barak, Henik, Gurman, & Stiener, 2002) learning tasks. In the former study, correct recognition of emotionally arousing pictorial stimuli after 3 weeks was associated with enhanced amygdala activation during presentation. These data can be interpreted as suggesting that the physiological processes induced by viewing emotional stimuli enhanced the later recollection of those stimuli. Although the current study involved testing students during a phase of chronic stress, while those cited above involved acute hormonal or emotional stimuli, it is probable that a common arousing mechanism related to limbic and reticular activation underlies these facilitatory effects. Indeed, elevated cortisol levels were reported in students during examination stress in comparison to the levels at the beginning of the academic year (Malarkey et al., 1995). In the present study we did not monitor cortisol levels, as we tested the students in different seasons (i.e., 3 months apart) and could exert no control over variables, such as sleep cycles and nightshift work. The advantage to naturalistic stressors is their ecological validity, as opposed to laboratory induced stressors; however, future studies on the mechanism of the performance facilitation would require control over food, caffeine, nicotine, and drug intake and sleep patterns, all of which can be erratic in a working student population. For example, although enhanced performance on a memory task in students prior to examinations, compared to the beginning of the semester, was reported by Vedhara et al. (2000), the cortisol levels during the exam period were actually decreased, possibly due to seasonal changes. Since we could not distinguish between the affective and arousing components of the exam stress in the present study, future research should compare the effects of alerting stimuli, such as that used by Meiran and Chorev (2005) and a stressful or fearful stimulus in the same experiment.

Almost all of the participants were women, in keeping with the proportion of female:male students in the department. Because males and females have different physiological and behavioural responses to stress (Canli et al., 2000; Wolf et al. 2001; Wood & Shors, 1998), we calculated the effect size in the sample of women only, compared to that of the entire sample and found similar effects. Further research would be required to determine if stress facilitates cognitive function differently in men and women. In summary, examination stress in students showed a facilitatory effect on two executive function tasks which manifested itself as a reduction in simple reaction time in the Stroop paradigm and a reduction of the slow reaction times induced by the switching cost in the spatial task-switching paradigm. This effect of chronic, but controllable stress, is similar to the effect of emotional arousing stimulus, or administration of exogenous analogues of the adrenal stress hormone on learning and memory tasks.

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