Acta Psychologica 202 (2020) 102980

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Beneficial effect of task-irrelevant threat on response inhibition

Jong Moon Choi*, Yang Seok Cho

Department of Psychology, Korea University, South Korea

ARTICLE INFO

Keywords:
Threat
Response inhibition
Stop-signal task
Electric shock
Inhibitory control

ABSTRACT

It is widely accepted that task-irrelevant threats utilize processing resources, resulting in impaired cognitive processes. However, if some subcomponents of the cognitive processes are activated by a threat, these cognitive processes may be facilitated. In the present study, we investigated whether task-irrelevant threats enhance cognitive control if the threat and task-relevant processes commonly recruit a cognitive process, inhibitory process. To examine the impact of task-irrelevant threats on inhibitory control, we had participants perform a stop-signal task with mild electric shocks. They were at risk for receiving the shocks randomly in threat blocks while no such shock was administered in safe blocks. The results showed that the stop-signal reaction time decreased under threat compared to safe conditions, indicating that inhibitory control was enhanced under threat. This beneficial effect of threat on response inhibition was more evident in participants with high state anxiety. An additional measurement of motor execution indicated that the interaction between threat and response inhibition was not derived from general arousal under threat. Results suggest that emotion and cognition do not interact simply by sharing processing resources but are related more closely to each other than we have previously thought by engaging a common processing.

1. Introduction

In complex environments, individuals need to adjust their behaviors appropriately based on environmental changes. While driving a car, for example, pressing the gas pedal is a proper behavior most of the time, but it is not appropriate when a traffic light turns red. To keep pursuing a goal (e.g., driving home safely), the familiar but inappropriate behaviors in a given situation have to be adjusted, and cognitive control plays a key role. Occasionally, however, cognitive control does not function successfully in the flames of emotion (e.g., road rage), suggesting that cognition can be affected by emotional state.

As depicted with a "road rage" example, it is generally assumed that aversive emotion is detrimental to cognition, especially when the emotion is not related to the goal at hand. In laboratory environments, abundant evidence has revealed that task-irrelevant aversive emotion interferes with cognitive functions. For instance, Verbruggen and De Houwer (2007) had participants perform a stop-signal task, in which an emotional or neutral picture was presented at the beginning of each trial. Their results showed that inhibitory control over prepotent responses was impaired when an emotional picture (negative or positive) was presented compared to a neutral picture. The interference of task-irrelevant emotion was also observed while participants discriminated the orientation of a triangle following emotional pictures (Hartikainen, Ogawa, & Knight, 2000). It was also seen in tasks requiring higher cognitive functions, such as judgment or reasoning (Blanchette & Richards, 2010) or decision-making (Starcke & Brand, 2012). In other studies, potential threats were used to induce aversive emotions such as stress or anxiety. For instance, in Shackman et al. (2006), mild electric shocks were administered independently to the performance of a visuospatial working memory task. Their results showed that participants committed more errors under the threat of shock than without such a threat. In another study with a picture-word interference task, the amount of the interference effect was greater under the threat of shock than under safe condition (Choi, Padmala, & Pessoa, 2012).

According to some theoretical frameworks, aversive emotion impairs cognitive functions by utilizing processing resources that are shared with cognitive functions. Attentional control theory (Eysenck, Derakshan, Santos, & Calvo, 2007) suggests that attentional resources are more likely to be allocated to whatever induces anxiety. The sources of anxiety could be either external (e.g., a threatening face) or internal (e.g., worrisome thoughts). Even if threat-inducing anxiety is not present, attentional resources are distributed widely rather than focused on a specific stimulus. Given the limited capacity of resources, anxiety reduces the availability of attentional resources to cognitive processes, resulting in the impairment of cognitive functions. Similarly, the dual-competition model (Pessoa, 2009) suggests that threat interferes with

---

* Corresponding author at: Department of Psychology, 145 Anam-ro Seongbuk-gu, Seoul 02841, South Korea.
E-mail addresses: psypaz@korea.ac.kr (J.M. Choi), yscho_psych@korea.ac.kr (Y.S. Cho).

https://doi.org/10.1016/j.actpsy.2019.102980
Received 28 June 2019; Received in revised form 25 September 2019; Accepted 22 November 2019

the competition for processing resources between subcomponents of information processing in perceptual and executive levels. In highly threatening circumstances, processing resources are not allocated to appropriate cognitive processes that are recruited for successful task performance.

The concept of shared resources implies that cognitive and emotional systems are intertwined loosely. It assumes that the interaction between cognition and emotion is mediated by shared processing resources, not by sharing processes per se. By contrast, Gray (2004) and Gray, Braver, and Raichle (2002) argued that cognition and emotion are integrated in a relatively strong manner. This integration does not, however, mean that cognitive and emotional systems are unified. Rather, it implies that cognitive and emotional systems are inseparable at some point in the stream of information processing. According to this integration account, it is assumed that behavior is biased toward a specific mode in a certain emotional state, adopting the cognitive system to situational demands, such as water-seeking when thirsty. Therefore, the cognitive processes that are consistent with the situational demands can be facilitated, whereas other cognitive processes that are not related to the situational demands are impaired.

The integration account does not exclude the resource accounts including attentional control theory or dual-competition model. If an emotional state (e.g., fear) is not related to a task goal (e.g., making a smile) at hand, the integration account predicts impaired task performance in parallel with the resource accounts. If an emotional state (e.g., fear) is related to a task goal (e.g., running away), on the other hand, the resource accounts maintain the prediction that a threat impairs task performance because of the utilization of processing resources by the processing of the threat. However, the integration account predicts that task performance will be enhanced under threat because cognitive processing, which is related to both the threat and task performance, is prioritized by the threat (Gray et al., 2002). Indeed, some empirical studies in laboratory environments showed that task performance can be enhanced under threat. For instance, Grillon and colleagues reported that anxiety induced by threat of shock enhanced motor inhibition and facilitated the successful stop of habitual responses (Cornwell, Echiverri, Covington, & Grillon, 2008; Grillon & Davis, 1997; Robinson, Krimsky, & Grillon, 2013). In the classic Stroop color-word task, the interference from task-irrelevant information was reduced by threat of shock (Hu, Bauer, Padmala, & Pessoa, 2012) or by exposure to an aversive odor (Finkelmeyer et al., 2010). In other research, stress from school exams reduced task switching costs (Kofman, Meiran, Greenberg, Balas, & Cohen, 2006), and stress induced by cold pressor stimulation increased dual-task performance (Beste, Yildiz, Meissner, & Wolf, 2013).

Interestingly, in studies that revealed the beneficial effects of a threat or stress, participants performed a cognitive task involving inhibition-related processes. Miyake et al. (2000) suggested three major executive functions: inhibition, shifting, and updating. Later, inhibition function was further divided into two types: response-distractor inhibition and resistance to proactive interference (Friedman & Miyake, 2004). Response-distractor inhibition is the ability to resist prepotent responses or interference from task-irrelevant information at hand. This function may be recruited during performance of stop-signal tasks or Stroop tasks. Resistance to proactive interference is the ability to resist interference from task-irrelevant information that was previously relevant. This function may be recruited during performance in a task-switching paradigm (Monsell, 2003). In sum, enhanced performance under threat in go/no-go tasks, Stroop tasks, and task-switching (e.g. Finkelmeyer et al., 2010; Kofman et al., 2006; Robinson et al., 2013) suggests that threats can enhance some subcomponents of inhibition-related processes, even if the threat is not directly related to task performance. However, to our knowledge, no study has addressed if task-irrelevant threat enhances inhibitory processes in cognitive functions. In a study, response inhibition under threat of shock was investigated with a go/no-go task (Robinson et al., 2013). The results revealed that the proportion of successful stops increased under threat compared to safe conditions. They suggested that anxiety induced by threat of shock promoted avoidance behavior from harmful stimuli, such as freezing. However, it is not clear if the increased no-go accuracy resulted from an inhibition of on-going responses. If a motor response was less likely to be initiated without a go signal in no-go trials (Verbruggen & Logan, 2009) or if anxiety induced by threat impaired motor responses globally, no-go accuracy would have been increased regardless of inhibitory processes of on-going responses.

In the present study, we hypothesized that task performance requiring inhibitory processes would be enhanced by a task-irrelevant threat if the inhibitory processes were prioritized by the threat during task performance. To investigate the hypothesis, we had participants perform a stop-signal task with or without the threat of electric shock. The threat was manipulated in a blocked fashion. Participants were informed about the block type by a visual cue at the beginning of each block. In safe blocks, no electric shock would be administered. In threat blocks, however, electric shocks were delivered randomly without the awareness of participants about the timing and frequency of shock administration. The number of electric shocks was set to twelve in an experiment to prevent participants from adaptation to the shock. However, the infrequent event of shocks may surprise participants, leading to suppression of motor responses (Wessel & Aron, 2017). To minimize this possibility, the shock was delivered 750 ms earlier than the target onset because the motor suppression by unexpected events was supposed to have a relatively short life of < 150 ms (Wessel, 2017). In addition, trials with electric shock were excluded from analyses so that we were able to examine the impact of threat on task performance without the issue of attentional allocation to the shocks (Shackman et al., 2006).

To examine the inhibitory control modulated by the threat, a stop-signal task was conducted. The stop-signal task is widely used to test the effortful inhibition of responses. Although the go/no-go task is also considered as a means to recruit a similar inhibitory mechanism, the stop-signal paradigm is more attractive because: (a) it is relatively free from an association of stopping response to stop or no-go stimuli, (b) it is considered to require relatively controlled suppression of an initiated response, and (c) it provides measurements to estimate the latency of the inhibitory processing, which is indexed by stop-signal reaction time (Verbruggen & Logan, 2009).

In the stop-signal paradigm, participants are typically instructed to discriminate a target stimulus (e.g., circle or square). Occasionally, however, a stop-signal (e.g., an auditory tone) is presented after a variable delay from the target onset (i.e., stop-signal delay [SSD]). When the stop-signal is presented (stop trials), participants are required to withhold the ongoing response. In the trials without the stop-signal (go trials), participants are encouraged to respond fast and accurately. According to the horse-race model (Logan & Cowan, 1984), successful inhibition of response is dependent on a race between go-process (starting at the onset of the target) and stop-process (starting at the onset of the stop-signal). A response cannot be withdrawn if the go-process is completed before the stop-process. In contrast, the response is successfully canceled if the stop-process wins the race, even though the stop-process started late as much as SSD. It is impossible to directly measure the latency of the stop-process because no response is executed when the stop-process wins the race. However, this stop-signal reaction time (SSRT) can be estimated by comparing the start and finish times of the stop-process. If responses are perpetrated with 40% of probability on stop trials, for example, it indicates that the go-process wins the race on 40% of the no-go trials while the stop-process does on 60% of them. Accordingly, we can assume that the race between go- and stop-processes results in a tie at the 40th percentile of possible response times (RTs). This possible RT distribution can be obtained based on the responses on go trials. Thus, the finish time for the stop-process as well as the go-process would be correspondent to the 40th percentile of the RT distribution of go trials. The stop-process started late as much as SSD so that SSRT can be estimated by subtracting SSD from the 40th percentile of the RT distribution on go trials. However, if SSD is fixed, participants might wait for the stop-signal intentionally. There are several methods suggested to prevent response strategies, but it is most common to adjust SSD dynamically based on a participant's performance (Verbruggen et al., 2019). For instance, if a participant stopped successfully on a stop trial, SSD is increased by 50 ms on the next stop trial, making it harder to stop. Otherwise, SSD is decreased by 50 ms on the next stop trial, making it more comfortable (see Materials and methods). By tracking performance and explaining the procedure to participants explicitly, they would be less likely to use the response strategy delaying responses intentionally.

The main purpose of the present study was to examine if a task-irrelevant threat would enhance response inhibition. According to the resource accounts (Eysenck et al., 2007; Pessoa, 2009), emotional states induced by threat of shock impede the allocation of processing resources. Thereby, response inhibition would be impaired under threat, resulting in longer SSRT. However, if inhibitory control of ongoing responses is prioritized under threat, as predicted by the integration account (Gray et al., 2002), SSRT would be smaller in threat blocks than safe blocks.

Alternatively, it is possible that SSRT modulation by threat is derived from general arousal under the threat of shock. SSRT is computed by subtracting the starting time of stopping process (i.e., stop-signal delay) from the finishing time, which is estimated based on RT distribution in go trials (see Data analysis section). If arousal by threat simply facilitates motor execution, for example, RT would be shorter under threat than safe. Then, SSRT would decrease under threat than safe even if the response inhibition was minimally affected by the threat. To test the hypothesis, we differentiated movement time (MT) from RT by adding a “home button” in response discrimination. It has been suggested that MT is less likely to be affected by cognitive manipulation (Doucet & Stelmack, 1997). Thus, we would observe MT modulation if there was any arousal effect by threat in the current study.

Finally, it has been reported that individual anxiety level modulates task performance of both non-emotional and emotional tasks (Eysenck et al., 2007; Williams, Mathews, & Mac Leod, 1996). To test the impact of individual differences in anxiety level on threat processing and response inhibition, we collected self-reported anxiety scores with the Korean version of the State-Trait Anxiety Inventory (Lee, 1994; Spielberger, 1983).

2. Materials and methods

2.1. Participants

To detect the difference in SSRT depending on emotion with a power of $1 - \beta = 0.95$ at an $\alpha = 0.05$, a power analysis using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009) for paired *t*-test required 26 participants. This sample size assumed an effect size of $d_z = 0.737$, based on a similar experiment by Verbruggen and De Houwer's (2007) Experiment 1. Given a possible difference in the effect-size estimation, a larger number of participants were recruited.

In total, thirty-three participants (16 male, 17 female; age range: 18–28 years old, $M = 22.6$) were recruited via a community webpage for Korea University students. They were compensated 6000 KRW (about 6 USD) for their participation and provided informed written consent, as approved by the Institutional Review Board of Korea University (1040548-KU-IRB-16-160-A-1). Participants were free from psychiatric or neurological disease or related history, as indicated via a self-report. They also had normal or corrected-to-normal vision.

2.2. Stimuli and apparatus

Stimuli presentation and response recording were controlled by Psychophysics Toolbox Version 3 (http://www.psychtoolbox.org/), implemented in MATLAB 2008a (The MathWorks, Natick, MA, USA). Behavioral responses were made with the right index finger using three keys (“2,” “5,” and “8”) on a standard numeric keypad of a regular PC keyboard. The buttons “2” and “8” were for the target, and “5” served as the home button (see Procedures section). The buttons were aligned longitudinally to minimize the possibility of participants using multiple fingers in responding.

All visual stimuli were presented at the center of the screen. The ready-sign (“준비”; “ready” in Korean; 2.2° × 1.2°) was in white. A white cross (1.1° × 1.1°) served as the fixation point. A target stimulus was either a circle (4.6° in diameter) or a square (4.6° × 4.6°) in white. A stop-signal was red ([255, 0, 0] in RGB) filled in a target stimulus. A mild electric shock was administered for 250 ms with an electric stimulator (Coulbourn Instruments, PA, USA) on the ring and small fingers of the left hand. The shock intensity was adjusted for each participant after a practice session. In total, 12 physical shocks were randomly delivered during the experiment (three to five shocks in each threat block), with an equal chance in the go and stop trials. The participants were not informed of the number of shocks. To ensure threat manipulation, skin conductance responses (SCRs) were collected at a sampling rate of 200 Hz using PowerLab 4/30 amplifier with ML116 GSR Amp (ADInstruments). Prior to the experiment, a pair of GSR finger electrodes (MLT116F) was attached to the index and middle fingers of the left hand. Recordings were performed with LabChart v7 software. All the behavioral and SCR data analyses were performed with MATLAB 2014b (The MathWorks, Natick, MA, USA) if not otherwise specified.

3. Procedures

3.1. Practice session

Participants performed 64 trials of a stop-signal task without the shock. The stop-signal was randomly (25% of stop-signal) presented in 16 trials. The purpose of the practice session was to make participants familiar with the task and to calibrate the RT window for each participant to respond correctly and rapidly (see below). By setting the RT window individually, we attempted to minimize the possibility of participants waiting for a stop-signal.

Each trial started with a ready-sign (Fig. 1.A). Participants were instructed to press and hold the home button until the target display appeared. If they released the home button before the target onset, the trial was aborted with a message reminding them to hold the button. The ready-sign was removed from the screen after 500 ms of the home button being pressed, and a fixation point was followed. The fixation was on the screen for a variable time (1000–2500 ms, mean 1400 ms) to prevent participants from anticipating the target onset as well as an electric shock in the main session. After the fixation, a target stimulus was presented. Participants were instructed to move their index finger from the home button to the correct target button before the target disappearance.

In go trials, the target duration was initially 680 ms. However, it was adjusted dynamically during the practice. If a participant responded correctly before the target disappearance in two consecutive go trials, the target duration was decreased by 34 ms for the subsequent go trial. Otherwise, the target duration was increased by 34 ms. The participants were not informed of the stair-casing procedure.

In stop trials, a target stimulus was presented for 1500 ms. However, the target was filled in red (stop-signal) after a variable SSD relative to the target onset. Participants were instructed not to press a target button when the stop-signal was presented (releasing the home button was tolerated). SSD was titrated during the practice. If a participant stopped responding to the target successfully on a stop trial, SSD was increased by 34 ms for the subsequent stop trial, making him/her harder to stop responding. Otherwise, SSD was decreased by 34 ms for the subsequent stop trial, making him/her more comfortable to stop

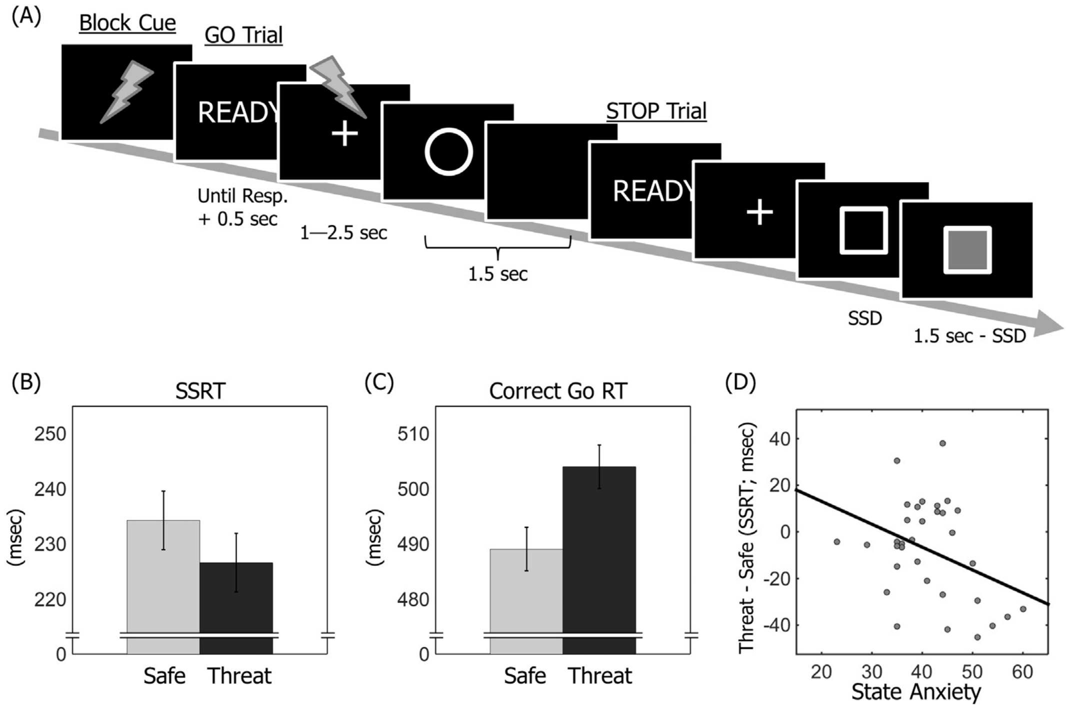

Fig. 1. (A) Experimental design. In each trial, a message instructing to hold the home button was presented in Korean. After a variable time, a target stimulus (circle or square) was displayed briefly in Go trials. In Stop trials, the target shape was filled in red color (stop-signal; presented in gray in the figure) after stop-signal delay (SSD) which was adjusted dynamically during experiment. (B) Estimated SSRT during safe and threat blocks. (C) Mean of response time in correct Go trials during safe and threat blocks. (D) Relationship between state anxiety scores and SSRT difference (threat – safe). Each data point corresponds to individual state anxiety score and SSRT difference. The gray line indicates the robust linear regression fit. Error bars in panels (B) and (C) denote 95% confidence interval after excluding between-subject variability (Loftus & Masson, 1994).

responding. Initial SSD was 204 ms.

In go and stop trials, feedback was presented after 1500 ms from the target onset. The feedback was displayed for 1000 ms after slow responses (i.e., responses after target disappearance; "늦었습니다"; "too slow" in Korean) or wrong responses ("틀렸습니다"; "wrong" in Korean) in go trials and unsuccessful stopping in stop trials ("누르지 마세요"; "do not press" in Korean). After the feedback display, the ready-sign was presented for the next trial.

3.2. Shock calibration session

To set the intensity of the electric shock for each participant, participants experienced several test shocks after their practice session. During the calibration, the shock intensity was increased step by step from the lowest intensity, and they were asked to choose their own intensity of shock such that the stimulation would be "highly unpleasant, but not painful." After each threat block, participants were asked about the unpleasantness of the shock, and, if needed, the shock intensity was adjusted to keep the level of the unpleasantness relatively constant.

3.3. Main session

The main session consisted of three safe (S) and three threat (T) blocks presented alternatingly starting with a safe block (i.e., S-T-S-T-S-T). Each block consisted of 64 trials (384 trials in total with 25% of stop-signal). At the beginning of each block, a visual display informing participants about the chance of electric shock was displayed until the home button was pressed. Participants were informed that electric shocks would be delivered randomly during threat blocks only.

The trial sequence was identical to the sequence during the practice except for the following. (a) The target duration of go trials was fixed during the main session. It was determined by computing the 75th percentile of the last 15 target durations of the correct go trials in practice (mean 584 ms across participants). (b) SSD was adjusted dynamically for safe and threat blocks, separately. However, the initial SSDs for both conditions were identical to the last SSD recorded during the practice session. (c) Performance feedback was not displayed. (d) Occasionally, an electric shock was administered 750 ms before the target onset. The number of shocks in a threat block was variable from three to five, with a total of 12 during the main session.

4. Data analysis

4.1. SCR data

Raw SCR data from each participant were initially detrended and smoothed with a median filter over 40 samples (200 ms) to reduce high-frequency noise, and resampled at 1 Hz. The pre-processed SCR time series data were analyzed using multiple linear regression using the AFNI software package (Cox, 1996, http://afni.nimh.nih.gov/afni) in a similar way as fMRI data (for related approaches, please see Choi et al., 2012). For each participant, SCRs were modeled for 15 s, starting from the onset of physical shock without any assumptions about the shape of the SCR (cubic spline basis functions). The goal of the analysis was to estimate SCRs without the impact of physical shock. Thus, the residual time series after modeling the physical shock were averaged for the safe and threat blocks separately.

4.2. Estimation of SSRT

The safe and threat blocks were alternated, starting from a safe block. To test if any order effect interacted with the threat effect, we analyzed the interaction between Block Order (1st, 2nd, and 3rd) and Block Type (safe and threat) on SSRT. However, results did not show an interaction between Block Order and Block Type ($F_{2,64} = 0.85$,

$p = .432$). Thus, in the rest of our analyses, we investigated the impact of threat on task performance by conducting paired t-tests on both go and stop trials without considering Block Order.

The time course of the inhibitory process was indexed with SSRT, which describes the time required to cancel an ongoing response. Shock trials proceeded by a physical shock (six in stop trials and six in go trials) and go trials with no response (i.e., RT = 0; 1.66% of the total go trials on average) were excluded from the analysis. To estimate SSRT, we used an integration method that is relatively secure from slowing responses and skewness of the RT distribution (Verbruggen, Chambers, & Logan, 2013). SSRTs for safe and threat conditions were computed separately as follows: (a) Find the finishing time of the stop-process, which corresponds to the nth fastest RT of go trials in each condition. (b) n is the product of the total number of go trials in a condition and the probability of responding on stop trials of the condition. For example, with 144 go trials and 0.5 response rate of stop trials in threat blocks, n is 72, indicating that go- and stop-processes are completed simultaneously at the 72th fastest go RT under threat; (c) the start of the stop-process is delayed from the go-process start as much as SSD, so mean SSD is subtracted from the nth RT for each condition (e.g., $\text{SSRT}_{\text{THREAT}} = n\text{th RT}_{\text{THREAT}} - \text{mean SSD}_{\text{THREAT}}$).

4.3. *MT, RT, and error rates*

If the threat simply affected motor execution, RT could be sped up or slowed down without a change in cognitive processes, resulting in underestimation or overestimation of SSRT in threat (Verbruggen et al., 2013). To test the impact of threat on motor execution independently from the cognitive process, we differentiated MT (latency from releasing the home button to pressing the target button) from RT (latency from target onset to pressing the target button). It should be noted that, in the studies using the “home” button, RT normally denotes reaction time (from the target onset to releasing the home button). The sum of reaction time and movement time is denoted as total time (TT), which corresponds to RT in the current study. Instead of using TT, we used RT in the current study to maintain consistency with other studies using the stop-signal paradigm.

For statistical analyses of MT, RT, and error rates, shock trials preceded by a physical shock were not included in the analyses. Additionally, go trials with RT exceeding three standard deviations from the condition-specific mean were also excluded for each participant (1.04% of the total go trials on average). For RT and MT analyses of go trials, error trials were excluded. Note that the trials with correct but slow responses (i.e., correct response after target disappearance) were included in analyses.

Table 1
Summary of behavioral data.

		Means		SDs	
		Safe	Threat	Safe	Threat
Stop trials	%Error	47.63	46.92	2.97	3.78
	Unsucc RT**	443	462	70	81
	Unsucc MT	130	132	35	33
Go trials	%Error	3.04	2.98	2.40	2.44
	Correct RT**	489	504	82	84
	Correct MT	144	144	38	37
	SSD**	243	264	87	86
	SSRT*	234	227	23	21

Note: MT, movement time (ms); RT, response time (ms); SD, standard deviation; SSD, stop-signal delay (ms); SSRT, stop-signal reaction time (ms); Unsucc, unsuccessful.

* $ps < .05$.

** $ps < .01$.

4.4. *Relationship with anxiety level*

One of the research interests in the current study was to investigate the relationship of task performance with individual differences in anxiety level. We had a relatively small sample size, and standard Pearson correlation is known to be sensitive to the so-called outliers. Thus, we ran robust regression analyses by employing the *robustfit* function in MATLAB (MathWorks, Natick, MA, USA), which uses iteratively reweighted least squares. The impact of threat was indexed by computing the difference between threat and safe conditions.

5. Results

5.1. *SCR data*

The mean SCR was greater during the threat blocks compared to the safe blocks (−0.56 μS vs. 0.21 μS for safe and threat blocks, respectively). This data provided evidence for successful threat manipulation, resulting in increased arousal, $t_{32} = 4.54, p < .001$, Cohen's $d = 1.50$.

5.2. *Behavioral data*

We investigated the impact of threat on task performance by conducting paired t-tests on both go and stop trials. Results of behavioral data are summarized in Table 1.

As we targeted, error rates of stop trials were close to 50% in safe blocks (47.63%) and threat blocks (46.92%), and did not show statistical difference, $t_{32} = 1.13, p = .268$. The independence assumption between go- and stop-processes was tested by contrasting the mean RTs of go trials and unsuccessful stop trials separately for the safe and threat conditions. In the safe condition, participants responded faster on stop trials than on go trials (443 ms vs. 492 ms), $t_{32} = 14.02, p < .001$, Cohen's $d = 2.44$.[1] Likewise, in the threat condition, unsuccessful stop RT on stop trials was faster than RT on go trials (462 ms vs. 508 ms), $t_{32} = 13.36, p < .001$, Cohen's $d = 2.15$. The results showed that the independence assumption of the horse-race model was not violated, and the estimated SSRT was reliable in the current study.

Of interest, SSRT was reduced under threat of shock than under safe conditions ($t_{32} = 2.08, p = .046$, Cohen's $d = 0.36$), indicating that the inhibitory process of ongoing responses was more efficient under threat than under safe conditions (Fig. 1.B). Consistent with SSRT, SSD was elongated under threat of shock compared to safe conditions ($t_{32} = 5.60, p < .001$, Cohen's $d = 0.98$), implying that participants were able to withhold their responses successfully under threat of shock even when the stop-signal was presented later than under safe condition.

The mean RT was longer in threat blocks than safe blocks on correct go trials ($t_{32} = 5.46, p < .001$, Cohen's $d = 0.95$), indicating that visual discrimination was impaired under threat (Fig. 1.C). The impact of arousal by threat on motor responses was not evident because mean MTs on correct go trials were not modulated by threat ($t_{32} < 0.01$, $p = .996$). The error rate on go trials did not show difference between safe and threat blocks ($t_{32} = 0.17, p = .866$).

5.3. *Relationship with anxiety level*

Robust regression analyses revealed that state anxiety scores have an inverse relationship with SSRT difference between threat and safe conditions ($t_{31} = -2.07, p = .047$, Cohen's $f^2 = 0.21$[2]), implying that participants with higher scores in state anxiety were more likely to withhold their responses than those with lower scores when the shock was anticipated (Fig. 1.D). Further analyses exploring which condition

---

[1] Cohen's d = t-score / (square root of [the number of participants]).

[2] Cohen's $f^2 = R^2 / (1 - R^2)$.

drove the relationship between anxiety and SSRT showed that the relationship was evident in threat blocks ($t_{31} = -3.09, p = .004$, Cohen's $f^2 = 0.84$) but not in safe blocks ($t_{31} = -0.07, p = .948$). RT difference between threat and safe blocks on correct go trials also showed an inverse relationship with state anxiety scores ($t_{31} = -2.95$, $p = .006$, Cohen's $f^2 = 0.31$). However, correct go RT was moderately modulated by state anxiety level in safe blocks ($t_{31} = 1.94$, $p = .062$, Cohen's $f^2 = 0.21$), but not in threat blocks ($t_{31} = 1.38$, $p = .178$).

Trait anxiety scores showed a positive relationship with MT difference between threat blocks and safe blocks on correct go trials ($t_{31} = 2.70, p = .011$, Cohen's $f^2 = 2.23$), indicating that participants with higher trait anxiety suffered more severely from the threat in executing motor responses. However, we could not find evidence specifying whether safe conditions or threat conditions drove the relationship between trait anxiety and MT ($ts_{31} = -0.22$ and 0.85, $ps = .830$ and .401 for safe and threat, respectively). No other relationship was observed.

6. Discussion

Based on the resource accounts, it was hypothesized that the threat of shock would impair response inhibition, resulting in longer SSRT in threat than safe blocks, because the threat would impede the allocation of processing resources to inhibitory control. However, in the present study, SSRT was decreased in threat conditions compared to safe conditions. The shorter SSRT did not seem to be attributed to a heightened arousal level under threat because MT on correct go trials was not affected by threat. Additionally, our robust regression analysis did not show any relationship of SCR with others (e.g., $\text{SCR}_{[\text{Threat} - \text{Safe}]}$ with $\text{SSRT}_{[\text{Threat} - \text{Safe}]}$; $t_{31} = 0.90, p = .377$). Therefore, the decreased SSRT in threat blocks indicates that inhibitory control over ongoing responses was enhanced under threat of shock.

Gray (1990) suggested that there are two motivational systems: the behavioral inhibition system (BIS) and the behavioral activation system (BAS). The BAS, which is sensitive to signals of reward, facilitates behaviors that may result in an appetitive outcome. The BIS, on the other hand, is sensitive to signals of punishment, non-reward, and novelty. It inhibits behaviors that may result in an aversive outcome. Under risk of receiving an aversive outcome, such as electric shocks in the present study, the motivational system may be biased toward the BIS, which inhibits responding to the target stimulus and facilitates withdrawal of ongoing responses. Thus, the results in the present study suggest that cognitive control can be enhanced if cognitive demands by task goal are consistent with emotional demands under threat. More broadly, the results imply that cognitive and emotional systems interact with each other by sharing specific components rather than sharing processing resources.

Additionally, we observed that the impact of threat on behaviors was modulated by individual differences. The capability to withhold ongoing responses was greater in participants with high state anxiety scores compared to those with low state anxiety scores. The state anxiety scores from the STAI questionnaire reflect relatively transient and context-specific states of anxiety (Spielberger, 1983). Thus, the BIS was activated by threat more greatly in the participants who were more sensitive to the threat (i.e., higher state anxiety scores) compared to those with low anxiety, resulting in greater enhancement of response inhibition under threat. By contrast, the trait anxiety score, which is more closely related to tonic and dispositional anxiety, revealed a positive relationship with MT difference in threat and safe conditions. Motor movement during task performance slowed with increase of trait anxiety scores, consistent with attentional control theory (Eysenck et al., 2007). These results suggest that behaviors and related processes can be modulated differently depending on the type of anxiety (Pacheco-Unguetti, Acosta, Callejas, & Lupiáñez, 2010).

Previously, the impact of task-irrelevant emotion on response inhibition has been investigated with a stop-signal task (Verbruggen & De Houwer, 2007). In line with the resource accounts, they observed that SSRT was prolonged when an emotional picture (negative or positive) was presented compared to a neutral picture. The results in Verbruggen and De Houwer seem to contradict the results of the present study. However, in their study, the threat (i.e., a negative picture) appeared immediately before the onset of the target stimulus. The physical presence of an emotional picture could attract visual attention and hold it (Eysenck et al., 2007; Fox, Russo, & Dutton, 2002). Thus, the SSRT prolonged by an emotional picture revealed that the emotion impairs recruitment of attentional resources rather than impeding the inhibitory process. By contrast, in the present study, the threat was not presented visually, and the trials preceded by an electric shock were excluded from analyses. Therefore, the current results indicate that a threat can enhance inhibitory process if it does not affect other cognitive components such as attentional control. Taken together with the results from Verbruggen and De Houwer, the bi-directional effect of emotion on response inhibition suggests that emotional impact on cognitive processes has various characteristics depending on where the emotional impact takes place in the stream of information processing.

More similar to the present study, Robinson et al. (2013) reported that the accuracy of no-go trials was increased under threat while performing a variant of the go/no-go task. They argued that adaptive cognitive functions promoting harm avoidance are enhanced in threatening circumstances. As they noted, however, the increased accuracy rate on no-go trials could be due to an enhanced visual sensitivity under threat. If no-go stimuli were perceived more clearly under threat, responses would be less likely to be initiated, resulting in a higher accuracy on no-go trials. In contrast, in the stop-signal paradigm, the stop signal was preceded by a target stimulus, so a response was more likely to be initiated even on stop trials (Verbruggen & Logan, 2009). Thus, the present study provides relatively strong evidence that the inhibitory control of ongoing response could be enhanced under a task-irrelevant threat.

Nonetheless, the decreased SSRT under threat conditions in the present study might have been due to the enhanced visual sensitivity under threat (Li, Howard, Parrish, & Gottfried, 2008). The horse-race model assumes that the stop-process starts the race by the onset of the stop signal (Logan & Cowan, 1984). Technically, however, the stop-process would start after a stop-signal stimulus is recognized as the stop-signal (Verbruggen, Stevens, & Chambers, 2014) found that SSRT could be increased if the stop signal is presented in the peripheral or accompanied with a distractor, suggesting that the perceptual processing of the stop signal modulates response inhibition. In the other way, if the perceptual processing of the stop signal is facilitated, for instance by threat in the present study, the stop process started more promptly, resulting in shorter SSRT. However, it would not be only the stop signal in which perceptual processing was facilitated by threat. The processing of the target stimuli also should have been facilitated. In the present study, the shock administration was not selectively associated with the stop signal (i.e., there was an equal probability of shock administration on go and stop trials). Therefore, if the threat of shock facilitated perceptual processing, the mean RT should have been shorter in threat than safe blocks. However, the analysis of the mean RT of correct go trials showed longer RT in threat than safe blocks, indicating evidence against the possibility that the enhanced perceptual processing under threat resulted in the shorter SSRT.

In conclusion, the present study demonstrated that response inhibition was enhanced by threat of shocks, which is supposed to activate inhibitory processes. In threatening circumstances, inhibitory process is prioritized, and it consequently promotes response inhibition. More generally, the present study suggests that specific behaviors and related cognitive processes can be facilitated even by aversive emotion such as anxiety. Additionally, these findings support the idea that emotional and cognitive systems are not separable, and they are integrated down in the stream of information processing (Gray, 2004; Gray et al., 2002).

Declaration of competing interest

None.

Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2016R1C1B1016082).

References

Beste, C., Yildiz, A., Meissner, T. W., & Wolf, O. T. (2013). Stress improves task processing efficiency in dual-tasks. *Behavioural Brain Research, 252*, 260–265. https://doi.org/10.1016/j.bbr.2013.06.013.

Blanchette, I., & Richards, A. (2010). The influence of affect on higher level cognition: A review of research on interpretation, judgement, decision making and reasoning. *Cognition & Emotion, 24*, 561–595. https://doi.org/10.1080/02699930903132496.

Choi, J. M., Padmala, S., & Pessoa, L. (2012). Impact of state anxiety on the interaction between threat monitoring and cognition. *NeuroImage, 59*(2), 1912–1923. https://doi.org/10.1016/j.neuroimage.2011.08.102.

Cornwell, B. R., Echiverri, A. M., Covington, M. F., & Grillon, C. (2008). Modality-specific attention under imminent but not remote threat of shock: Evidence from differential prepulse inhibition of startle. *Psychological Science, 19*(6), 615–622. https://doi.org/10.1111/j.1467-9280.2008.02131.x.

Cox, R. W. (1996). AFNI: Software for analysis and visualization of functional magnetic resonance neuroimages. *Computers and Biomedical Research, an International Journal, 29*(3), 162–173.

Doucet, C., & Stelmack, R. M. (1997). Movement time differentiates extraverts from introverts. *Personality and Individual Differences, 23*, 775–786. https://doi.org/10.1016/S0191-8869(97)00104-9.

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion (Washington, D.C.), 7*(2), 336–353. https://doi.org/10.1037/1528-3542.7.2.336.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149.

Finkelmeyer, A., Kellermann, T., Bude, D., Nießen, T., Schwenzer, M., Mathiak, K., & Reske, M. (2010). Effects of aversive odour presentation on inhibitory control in the Stroop colour-word interference task. *BMC Neuroscience, 11*(1), https://doi.org/10.1186/1471-2202-11-131.

Fox, E., Russo, R., & Dutton, K. (2002). Attentional bias for threat: Evidence for delayed disengagement from emotional faces. *Cognition & Emotion, 16*, 355–379. https://doi.org/10.1080/02699930143000527.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology; General,* 101–135. https://doi.org/10.1037/0096-3445.133.1.101.

Gray, J. A. (1990). Brain systems that mediate both emotion and cognition. *Cognition & Emotion, 4*(3), 269–288. https://doi.org/10.1080/02699939008410799.

Gray, J. R. (2004). Integration of emotion and cognitive control. *Current Directions in Psychological Science, 13*(2), 46–48. https://doi.org/10.1111/j.0963-7214.2004.00272.x.

Gray, J. R., Braver, T. S., & Raichle, M. E. (2002). Integration of emotion and cognition in the lateral prefrontal cortex. *Proceedings of the National Academy of Sciences USA, 99*, 4115–4120. https://doi.org/10.1073/pnas.062381899.

Grillon, C., & Davis, M. (1997). Effects of stress and shock anticipation on prepulse inhibition of the startle reflex. *Psychophysiology, 34*(5), 511–517. https://doi.org/10.1111/j.1469-8986.1997.tb01737.x.

Hartikainen, K. M., Ogawa, K. H., & Knight, R. T. (2000). Transient interference of right hemispheric function due to automatic emotional processing. *Neuropsychologia, 38*, 1576–1580. https://doi.org/10.1016/S0028-3932(00)00072-5.

Hu, K., Bauer, A., Padmala, S., & Pessoa, L. (2012). Threat of bodily harm has opposing effects on cognition. *Emotion, 12*(1), 28–32. https://doi.org/10.1037/a0024345.

Kofman, O., Meiran, N., Greenberg, E., Balas, M., & Cohen, H. (2006). Enhanced performance on executive functions associated with examination stress: Evidence from task-switching and Stroop paradigms. *Cognition & Emotion, 20*(5), 577–595. https://doi.org/10.1080/02699930500270913.

Lee, Y. J. (1994). *Relations of stress, social support, and self esteem to depression and anxiety.* Doctoral ThesisSeoul: Seoul Women's University Postgraduate School.

Li, W., Howard, J. D., Parrish, T. B., & Gottfried, J. A. (2008). Aversive learning enhances perceptual and cortical discrimination of indiscriminable odor cues. *Science, 319*, 1842–1845. https://doi.org/10.1126/science.1152837.

Loftus, G. R., & Masson, M. E. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review, 1*, 476–490.

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review, 91*(3), 295–327. https://doi.org/10.1037/0033-295X.91.3.295.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100. https://doi.org/10.1006/cogp.1999.0734.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*, 134–140. https://doi.org/10.1016/s1364-6613(03)00028-7.

Pacheco-Unguetti, A. P., Acosta, A., Callejas, A., & Lupiáñez, J. (2010). Attention and anxiety: Different attentional functioning under state and trait anxiety. *Psychological Science, 21*(2), 298–304. https://doi.org/10.1177/0956797609359624.

Pessoa, L. (2009). How do emotion and motivation direct executive control? *Trends in Cognitive Sciences, 13*(4), 160–166. https://doi.org/10.1016/j.tics.2009.01.006.

Robinson, O. J., Krimsky, M., & Grillon, C. (2013). The impact of induced anxiety on response inhibition. *Frontiers in Human Neuroscience, 7*, 69. https://doi.org/10.3389/fnhum.2013.00069.

Shackman, A. J., Sarinopoulos, I., Maxwell, J. S., Pizzagalli, D. A., Lavric, A., & Davidson, R. J. (2006). Anxiety selectively disrupts visuospatial working memory. *Emotion, 6*(1), 40–61. https://doi.org/10.1037/1528-3542.6.1.40.

Spielberger, C. D. (1983). *Manual for the State-Trait Anxiety Inventory STAI (form Y) ("self-evaluation questionnaire")*.

Starcke, K., & Brand, M. (2012). Decision making under stress: A selective review. *Neuroscience & Biobehavioral Reviews, 36*(4), 1228–1248. https://doi.org/10.1016/j.neubiorev.2012.02.003.

Verbruggen, F., Aron, A. R., Bissett, P. G., Brockett, A. T., Brown, J. W., Chamberlain, S. R., … Thakkar, K. N. (2019). A consensus guide to capturing the ability to inhibit actions and impulsive behaviors in the stop-signal task. *ELife, 8*(e46323), 26. https://doi.org/10.7554/eLife.46323.

Verbruggen, F., Chambers, C. D., & Logan, G. D. (2013). Fictitious inhibitory differences: How skewness and slowing distort the estimation of stopping latencies. *Psychological Science, 24*(3), 352–362. https://doi.org/10.1177/0956797612457390.

Verbruggen, F., & De Houwer, J. (2007). Do emotional stimuli interfere with response inhibition? Evidence from the stop signal paradigm. *Cognition and Emotion, 21*(2), 391–403. https://doi.org/10.1080/02699930600625081.

Verbruggen, F., & Logan, G. D. (2009). Models of response inhibition in the stop-signal and stop-change paradigms. *Neuroscience & Biobehavioral Reviews, 33*(5), 647–661. https://doi.org/10.1016/j.neubiorev.2008.08.014.

Verbruggen, F., Stevens, T., & Chambers, C. D. (2014). Proactive and reactive stopping when distracted: An attentional account. *Journal of Experimental Psychology: Human Perception and Performance, 40*(4), 1295. https://doi.org/10.1037/a0036542.

Wessel, J. R. (2017). Perceptual surprise aides inhibitory motor control. *Journal of Experimental Psychology: Human Perception and Performance, 43*(9), 1585–1593. https://doi.org/10.1037/xhp0000452.

Wessel, J. R., & Aron, A. R. (2017). On the globality of motor suppression: Unexpected events and their influence on behavior and cognition. *Neuron, 93*(2), 259–280. https://doi.org/10.1016/j.neuron.2016.12.013.

Williams, J. M., Mathews, A., & Mac Leod, C. (1996). The emotional Stroop task and psychopathology. *Psychological Bulletin, 120*(1), 3–24.