RESEARCH REPORT

Can Arousal Modulate Response Inhibition?

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The goal of the present study was to examine if and how arousal can modulate response inhibition. Two competing hypotheses can be drawn from previous literature. One holds that alerting cues that elevate arousal should result in an impulsive response and therefore impair response inhibition. The other suggests that alerting enhances processing of salient events and can therefore enhance processing of a cue that indicates to withhold a response and improve response inhibition. In a stop-signal task, participants were required to withhold prepotent responses when a stop signal followed target onset. Abrupt alerting cues preceded the target in one half of the trials. The results showed that alerting improved response inhibition as indicated by shorter stop-signal reaction times following an alerting cue compared with a no-alerting condition. We conclude that modulation of low-level operations can influence what are considered to be higher cognitive functions to achieve optimal goal-directed behavior. However, we stress that such interactions should be treated cautiously as they do not always reflect direct links between lower and higher cognitive mechanisms.

Keywords: alerting, inhibitory control, response inhibition, arousal, stop signal

There is growing interest in the orchestration of various functions to secure efficient goal-directed behavior. This might involve what seem to be very different functions and brain systems. The present study examined a potential interaction between arousal and inhibitory control. The former is highly associated with subcortical brain systems and the latter with frontal brain regions.

An important feature of executive functions and perhaps a hallmark of these functions is inhibitory control (van Veen & Carter, 2006; Verbruggen & Logan, 2008); it represents the ability to control impulses and to prevent acting on irrelevant information. An important aspect of inhibitory control is the ability to overcome a prepotent response. To study this process, many researchers use the stop-signal task that allows measuring the ability to stop an already initiated action (Logan, 1994; Logan & Cowan, 1984). In the stop-signal task, participants perform speeded reactions to a visual stimulus (go signal) in a simple discrimination task. In one fourth of the trials, an auditory stimulus (stop signal) follows the go signal. It signals participants to inhibit their motor response. If the delay between the go signal and the stop signal (stop-signal delay; SSD) is relatively short, it is easier to stop a response compared to when the delay is long. The SSD is submitted to a tracking procedure and changes from one trial to the next based on the participant's success in inhibiting his or her response (i.e., a successful inhibition will cause the next trial to be more difficult—the SSD will be longer—and an unsuccessful inhibition will cause the next SSD to be shorter). Eventually, it is possible to estimate the stop-signal reaction time (SSRT), which is the time required for successful inhibition. Logan and Cowan (1984) and Logan, Cowan, and Davis (1984) compared the performance in the stop-signal task to a horse race between the more automatic go process, triggered by the presentation of the go signal, and the executive stop process, triggered by the stop signal.

The stop-signal task has been used extensively to study inhibitory control impairments in different populations and especially in obsessive–compulsive disorder (e.g., Chamberlain, Fineberg, Blackwell, Robbins, & Sahakian, 2006; Linkovski, Kalanthroff, Henik, & Anholt, 2013) and attention deficit/hyperactive disorder (for review see Verbruggen & Logan, 2008). Inhibitory control is highly associated with frontal brain regions and especially the right inferior frontal gyrus (e.g., Aron, Behrens, Smith, Frank, & Poldrack, 2007; Chambers et al., 2007).

An outstanding question is whether the ability to inhibit a response can be influenced by manipulating what seem to be unrelated or distant brain mechanisms. One example is the system that is responsible for modulating arousal.

Presentation of an alerting cue (i.e., an irrelevant external signal that appears briefly) can be used to increase arousal for a short period of time (i.e., phasic alertness). The behavioral effect of the alerting cue is reduced reactions times (RTs) compared with a no-cue condition (i.e., the alerting effect). The alerting process is modulated by the distribution of norepinephrine (NE) from the locus coeruleus (LC) in the brain stem (Aston-Jones & Cohen,

2005). Studies in healthy individuals and animals reported that when administrating drugs that reduce synaptic NE, smaller alerting effects were observed (Coull, Nobre, & Frith, 2001; Witte & Marrocco, 1997). This was considered evidence that NE release underlies the alerting effect.

When attempting to examine the possibility of an interaction between alerting and response inhibition, the literature provides mixed evidence. According to Posner (Posner, 1978; Posner & Petersen, 1990), the selection of response following an alerting cue occurs faster but is based upon a lower quality of information. This notion was inspired from findings reporting faster response following alerting cues, which was accompanied by more errors (Posner, 1978). According to this view, an alerting cue leads to increased readiness to respond, which in turn promotes a premature and impulsive response and can therefore impair the ability to stop an already initiated response.

In addition, studies repeatedly showed that alerting impairs a different aspect of inhibitory control—the ability to inhibit distractor interference (e.g., Callejas, Lupiàñez, Funes, & Tudela, 2005; Chica et al., 2012; Costa, Hernández, & Sebastián-Gallés, 2008; Dye, Baril, & Bavelier, 2007; Dye, Green, & Bavelier, 2009; Fan et al., 2009; Ishigami & Klein, 2010; MacLeod et al., 2010; McConnell & Shore, 2011; Redick & Engle, 2006; Weinbach & Henik, 2012). These studies used the flanker task, which requires participants to respond to a central target while attempting to ignore irrelevant distractors (i.e., flankers) in close proximity. Studies reported that following alerting cues, the flanker interference effect was increased compared with a no-alerting condition. Several researchers suggested that this effect reflects a direct negative impact of alerting on executive control (Callejas et al., 2005; Fan et al., 2009). Specifically, Callejas et al. (2005) suggested that alerting inhibits frontal brain regions that are involved in cognitive control. However, other studies suggested that alerting does not necessarily impair executive control directly (Böckler, Alpay, & Stürmer, 2011; Fischer, Plessow, & Kiesel, 2012; Nieuwenhuis & de Kleijn, 2013; Weinbach & Henik, 2012).

For example, in a recent study Nieuwenhuis and de Kleijn (2013) suggested that when alertness levels are high, the decision threshold is reached earlier. In addition, executive control is a process that takes time to develop. Thus, when the decision threshold is reached following an alerting cue, the executive process is still rather weak and impairment in executive measures is observed. In that sense, alerting does not directly inhibit frontal brain regions involved in executive control. According to this view, alerting should result in poor response inhibition in the framework of the stop-signal task. Specifically, in the stop-signal task, a decision to respond to a go signal is expected to be reached earlier following an alerting cue compared to no-cue trials. However, in the presence of a stop signal, aborting the already initiated response should be more difficult because the inhibitory process is not fully developed.

In contrast with evidence suggesting that alerting should result in impaired response inhibition, there are studies suggesting otherwise. For example, Weinbach and Henik (2014) recently demonstrated that alerting prioritizes perceptual processing of any salient information displayed in the visual field. It was shown, in accordance with previous reports, that alerting enhanced attention to task-irrelevant salient information (i.e., explaining the greater interference in the flanker task under an alert state). However, it

was also demonstrated that alerting could reduce distractor interference when the task-relevant information was more salient than the task-irrelevant information. Other studies have also shown the role of alerting in improving processing of task-relevant information; at the neural level, high alertness was recently associated with reduced activation in the primary visual cortex when processing a visual target, suggesting less neural effort required for perceptual processing under an alert state (Fischer, Plessow, & Ruge, 2013).

The impact of alerting on these perceptual processes should play a crucial role in response inhibition. Verbruggen, Stevens, and Chambers (2014) recently reported that response inhibition in the framework of the stop-signal task can be largely explained by modulations of perceptual processes. Specifically, they showed that when perceptual processing of the stop signal was more difficult, response inhibition was impaired. Therefore, it is possible that by improving perceptual processing and enhancing attention for salient relevant information, alerting can actually improve rather than impair response inhibition. In order to unravel the role of alerting in modulating response inhibition, we examined the ability to abort an already initiated response following alerting cues in a stop-signal task.

Alerting cues were introduced in half of the trials just before the appearance of a go signal (Figure 1 depicts a typical trial). We used SSRT as a measure of response inhibition and compared SSRT in trials that included an alerting cue with trials in which the alerting cue was absent. We predicted that alerting would generally result in faster RTs in go trials (i.e., the alerting effect). With respect to the SSRT, if alerting acts to impair the stopping process, then SSRT should be longer following an alerting cue compared with a no-alerting condition. The reverse pattern would be observed if alerting improves stopping. If alerting has no influence on response inhibition then SSRT should be comparable between the alerting and no-alerting conditions.

Method

Participants

Nineteen students, 13 women and six men, aged from 20 to 28 years old ($M = 24.6$ years, $SD = 1.7$) of Ben-Gurion University of
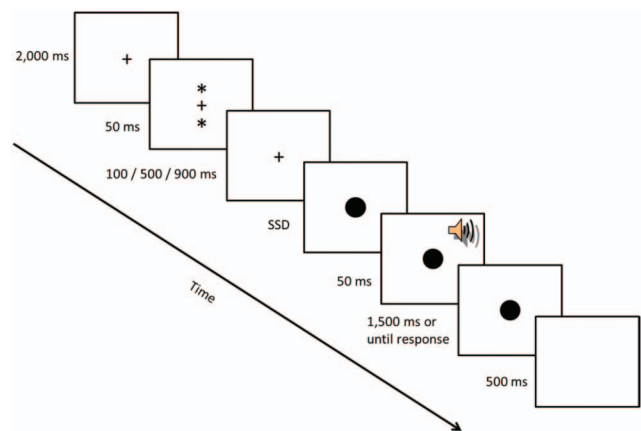

Figure 1. Example of a typical trial that includes an alerting cue and a stop signal following a circle target. See the online article for the color version of this figure.

the Negev (Israel) participated in the present study for a monetary payment. All participants had normal or corrected-to-normal vision, were right-handed, reported no history of attention deficit, and were naive as to the purpose of the experiment. One participant was excluded from the analysis due to misunderstanding of instructions.

Apparatus

Data collection and stimuli presentation were controlled by a DELL OptiPlex 760 vPro computer with an Intel core 2 duo processor E8400 3 GHz. Stimuli were presented on a DELL E198PF 19-inch LCD monitor. The participant sat approximately 23.62 in. from the computer screen. A headphone set was used to deliver auditory tones.

Stimuli

Each stimulus consisted of a white shape, presented on a black background, at the center of the screen. The shape was either a circle (1 cm in diameter) or a square (1 cm, squared). The stop signal was an auditory tone (750 Hz, 85 dB, 50 ms) delivered through a headphone set. The alerting cues that were used to increase arousal were made of two asterisks (0.5 cm in height and width, 0.85 cm from central fixation) that flashed briefly (50 ms) above and below the fixation point.

Procedure

Each trial started with a fixation point (a white "+" sign at the center of the screen; see Figure 1). In half of the trials (i.e., half of the go trials and half of the stop trials), 2,000 ms following the appearance of fixation, a visual alerting cue was presented for 50 ms. There were three possible stimulus onset asynchronies (SOA) between the appearance of the alerting cue and the go signal: 100 ms, 500 ms, and 900 ms. These time intervals were subjected to a nonaging foreperiod distribution in order to ensure that the alerting cue elicited arousal rather than temporal expectancy.[1] In the no-alerting trials, the time intervals were matched as if there was an alerting cue. Following the time intervals, the target (circle or square) appeared at the center of the screen for 2,000 ms or until response. Participants were instructed to hit the Z key of the keyboard with the index finger of their left hand if the stimulus was a square and the M key with the index finger of their right hand if it was a circle. In stop-signal trials (one quarter of the trials), a stop signal was presented after a variable SSD that was initially set at 250 ms and adjusted by a staircase tracking procedure—after each successful stopping the SSD was extended by 20 ms and after each unsuccessful stopping the SSD was shortened by 20 ms. SSD was adjusted for each alerting condition (with alerting/no-alerting) separately (e.g., after a successful stopping in an alerting cue trial, the SSD was extended only for the next alerting cue trial, not affecting the SSD for the no-alerting condition). In order to prevent the use of a waiting strategy, instructions emphasized reacting as fast as possible and avoiding waiting for the stop signal. The go signal remained on the screen for 1,500 ms after the stop signal, or until a response was received. Each trial ended with a 500 ms intertrial interval of a black, blank screen. RTs were calculated from the appearance of the go signal to the reaction.

The experiment included 24 practice trials and 372 experimental trials. Trials were presented in a random order. During practice, participants received feedback on accuracy and RT.

Results

Accuracy rate for the go trials in the discrimination task was 99% and 98% for the alerting and no-alerting condition, respectively. The percentage of erroneous response given a stop signal was nearly 50% (see Table 1), indicating that the tracking procedure was successful. Mean RTs for correct responses in go trials were calculated for each participant in each alerting condition (see Table 1). RTs were subjected to a two-way repeated measure analysis of variance (ANOVA) with alerting (alerting or no-alerting) and SOA (100, 500, or 900 ms) as within-subject factors. As expected, a main effect for alerting was found, $F(1, 17) = 33.43$, $MSE = 146.93$, $p < .001$, $\eta_p^2 = .66$. Mean RT in the alerting cue condition was faster than in the no-alerting condition. There was no main effect for SOA, $F(2, 34) = 1.55$, $MSE = 844$, $p = .22$, $\eta_p^2 = .08$, and no interaction between alerting and SOA, $F(2, 34) = 1.86$, $MSE = 474$, $p = .16$, $\eta_p^2 = .09$. Moreover, there was no effect for SOA following the alerting cue $F(2, 34) = 1.75$, $MSE = 849.69$, $p = .18$, $\eta_p^2 = .09$, indicating that the nonaging procedure was successful and that the alerting cues did not exert expectation for target appearance following a particular SOA.

As mentioned earlier, SSD was adjusted and SSRT was calculated for each participant in each alerting condition separately. SSRT was calculated using the integration method (Verbruggen & Logan, 2009)—go trial RTs were determined by the nth RT; that is, N (number of correct go trials) × P (response\signal), which was done for each alerting condition separately. SSRT was then calculated as the nth RT-median SSD. SSRT data were subjected to a one-way ANOVA, with alerting as a within-subject factor. SSRT was significantly faster in the alerting trials compared with a no-alerting condition, $F(1, 17) = 10.46$, $MSE = 557.01$, $p < .01$, $\eta_p^2 = .38$ (see Table 1).

Discussion

The results of the present study are straightforward. Abrupt alerting cues improved the ability to stop an already initiated response. In the stop-signal task, the SSRT was shorter in trials that included an alerting cue prior to the go signal compared with a no-alerting condition. This effect was accompanied by a reliable alerting effect (i.e., faster RTs in trials with alerting cues compared with a no-alerting condition) in the go trials (i.e., trials in which a stop signal was absent). Note that the SSD was the same in the alerting and no-alerting condition. This means that despite the fact that the go-process finished earlier following an alerting cue (i.e., faster responding to the go signal in the alerting compared with the no-alerting condition), participants were still able to obtain the same SSD as in the no-alerting condition. Hence, the difference in

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[1] Nonaging distribution of trials refers to manipulating the proportion of trials for each SOA to create equal probability for target appearance following each SOA. In this way the alerting cue does not provide any information regarding the temporal appearance of the target. A previous study showed that this procedure is useful to ensure that the alerting cue elicits arousal rather than top-down temporal expectancy (Weinbach & Henik, 2013).

Table 1
Results of Experiment 1

Statistic and trial	Trial type	
	With alerting	No alerting
M RT for go-signal trials (% errors)	512 (1.56)	535 (2.39)
Mdn SSD	270	270
SSRT (standard error of the mean)	218 (15)	243 (18)
% of erroneous responses to stop signal	47.09	46.16

Note. Reaction time (RT), stop-signal delay (SSD), and stop-signal reaction time (SSRT) in milliseconds.

SSRT between the alerting and no-alerting conditions can be attributed to processes related to successful stopping.

The present study provides evidence that high arousal induced by behavioral methods can improve stopping of an already initiated response. These results are in contrast with previous suggestions that alerting leads to impulsive response by lowering the response threshold (Posner, 1978). In addition, there was no difference in go-trial accuracy rates between the alerting and no-alerting conditions, which rules out speed–accuracy trade-offs. The results are also in contrast with arguments suggesting a direct negative impact of alerting on executive control (Callejas et al., 2005; Fan et al., 2009).

Reports regarding impaired executive control following an alerting cue were based on a ubiquitous finding from the flanker task showing larger interference from distractors following an alerting cue compared with a no-cue condition (for review see MacLeod et al., 2010). The ability to inhibit distractor interference (e.g., in the flanker task) and the ability to inhibit a prepotent response (e.g., in the stop-signal task) represent different aspects of inhibitory control (Diamond, 2013). This leaves open the possibility that alerting acts to directly impair interference control and to directly improve response inhibition. However, this is not likely for two main reasons: a) Although interference control and response inhibition represent different aspects of inhibitory control, they both share a similar neural basis (for review see Diamond, 2013) and factor analyses showed that they are highly correlated and represent a single factor (Friedman & Miyake, 2004). b) Alerting is a bottom-up mechanism that probably cannot selectively improve one aspect of inhibitory control and impair another.

Therefore, it seems much more likely that a single process underlies both reports of improved and impaired inhibitory control following an alerting cue. We believe that this single process is the ability of alerting cues to improve perceptual processing of salient information in the environment (Weinbach & Henik, 2014).

Specifically for the stop-signal task, we suggest that alerting improved extraction of perceptual information from the go and stop signals, resulting in improvement of both responding and stopping processes, respectively. In that sense, alerting does not seem to directly influence the inhibitory process per se. However, Verbruggen, McLaren, and Chambers (2014) recently suggested a theoretical framework according to which perceptual processes cannot be excluded from the concept of "response inhibition." Specifically, they suggested that response inhibition is comprised of several underlying basic processes and perceptual processing of the stimuli is a fundamental part of the inhibitory process. In a follow-up experimental work, they revealed that response inhibi-

tion in the framework of the stop-signal task could be largely explained by modulation of perceptual processes that were in charge of extracting the information from the go and stop signals (Verbruggen et al., 2014). We suggest that alerting cues in the current study facilitated these aspects of response inhibition; namely, alerting induced an efficient and faster extraction of perceptual information from the stimuli. This allowed faster responding to a target but also improved the ability to abort the response in the presence of the stop signal.

Perceptual processing of the environment seems to play an important role in how we eventually carry out goal-directed behavior. The current work emphasizes the role of basic processes and mechanisms in modulating what are considered to be complex and multifaceted mental operations, such as action control. This warrants caution when discussing direct interactions between lower and higher cognitive mechanisms such as alerting and executive control. Interactions between lower and higher mechanisms do not always reflect direct links. Hence, thorough investigations of underlying processes can provide a clearer and more complete understanding of how the work of the cognitive apparatus is orchestrated.

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