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Executive control suppresses pupillary responses to aversive stimuli

Noga Cohen*, Natali Moyal, Avishai Henik

Department of Psychology and the Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Beer-Sheva, Israel

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ABSTRACT

Adaptive behavior depends on the ability to effectively regulate emotional responses. Continuous failure in the regulation of emotions can lead to heightened physiological reactions and to various psychopathologies. Recently, several behavioral and neuroimaging studies showed that exertion of executive control modulates emotion. Executive control is a high-order operation involved in goal-directed behavior, especially in the face of distractors or temptations. However, the role of executive control in regulating emotion-related physiological reactions is unknown. Here we show that exercise of executive control modulates reactivity of both the sympathetic and the parasympathetic components of the autonomic nervous system. Specifically, we demonstrate that both pupillary light reflex and pupil dilation for aversive stimuli are attenuated following recruitment of executive control. These findings offer new insights into the very basic mechanisms of emotion processing and regulation, and can lead to novel interventions for people suffering from emotion dysregulation psychopathologies.

1. Introduction

"I don't want to be at the mercy of my emotions. I want to use them, to enjoy them, and to dominate them."
(Oscar Wilde, The Picture of Dorian Gray)

As is nicely emphasized in this citation of Oscar Wilde, although emotions are an essential part of our lives, we should be able to control them under specific situations. A vast amount of research shows that the processing of emotionally negative information is prioritized (Vuilleumier, 2005); negative stimuli facilitate perceptual processes (Phelps, Ling, & Carrasco, 2006) and memory consolidation (Paré, Collins, & Pelletier, 2002), grab one's attention (Fox, 2002), and interfere with decision making processes (Paulus & Yu, 2012). These behavioral effects are accompanied by physiological reactions such as elevated heart rate (HR) (Thayer & Lane, 2000), increased skin conductance response (SCR) (Esteves, Dimberg, & Öhman, 1994) and dilated pupils (Bradley, Miccoli, Escrig, & Lang, 2008). Limbic regions, especially the amygdala, play a role in emotional processing (Phelps & LeDoux, 2005). Although these behavioral and physiological reactions are crucial for survival under threatening situations, they may hinder adaptive behavior when the emotional information is irrelevant to current goals.

Recently, both behavioral and neuroimaging studies have suggested that executive control is a key component in involuntary emotion regulation (Iordan, Dolcos, & Dolcos, 2013; Okon-Singer, Lichtenstein-Vidne, & Cohen, 2013). Executive control is a high-order cognitive operation that enables goal-directed behavior by inhibiting the influence of distracting information on performance (Banich, 2009; Miller & Cohen, 2001).

Several cognitive tasks such as the Stroop (Stroop, 1935), Simon (Simon and Small, 1969), and Flanker (Eriksen & Eriksen, 1974) tasks can be used to trigger executive control. In these tasks, participants are presented with stimuli that are comprised of two dimensions: a relevant dimension (which participants are requested to respond to) and an irrelevant dimension (that participants need to ignore). Two types of stimuli are usually used: congruent and incongruent. In congruent stimuli the relevant and irrelevant dimensions lead to the same response, while in incongruent stimuli these dimensions lead to opposite responses. Thus, incongruent stimuli result in a conflict and executive control is recruited to resolve this conflict (Gratton, Coles, Sirevaag, Eriksen, Donchin, 1988; Norman & Shallice, 1980). This executive recruitment is manifested in slower reaction time (RT) for incongruent compared to congruent stimuli.

Recently, we demonstrated that recruitment of executive control during incongruent flanker stimuli results in reduced emotional interference (Cohen, Henik, & Mor, 2011; Cohen, Henik, & Moyal, 2012; Cohen, Mor, & Henik, 2015a; Cohen, Mor, & Henik, 2015b). In addition, several neuroimaging studies demonstrated that recruitment of brain regions associated with executive con-

* Corresponding author at: Department of Psychology, Ben-Gurion University of the Negev, P.O.B 635, Beer-Sheva 8410501, Israel. Fax: +972 8 6472072.
E-mail address: nogac@post.bgu.ac.il (N. Cohen).

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trol suppresses amygdala activity for emotional distractors (Iordan et al., 2013; Van Dillen & Koole, 2007). Thus, both behavioral and imaging data suggest that executive control can serve to attenuate emotional reactions.

The current study explored whether recruitment of executive control attenuates the physiological responses triggered by emotional stimulation, as indicated by pupillary responses. Pupillary measurement is commonly used to index both parasympathetic and sympathetic activations of the autonomic nervous system (ANS; Samuels & Szabadi, 2008a, 2008b). The Edinger–Westphal nucleus (EWN) of the parasympathetic branch controls pupil constriction through connections to the pupil constrictor muscle (Samuels & Szabadi, 2008a). Sympathetic activity controls pupil dilation through adrenergic receptors in the pupil dilator muscle. Activation of the parasympathetic system can be examined during the light reflex, in which the pupil automatically constricts in response to luminance change. Activation of the sympathetic system is examined by assessing pupil diameter during a dilation phase. Importantly, the length and magnitude of pupil dilation and light reflex cannot be controlled voluntarily. In the absence of external visual changes, pupil dilation can only be evoked by mentally imagining a stimulus or event that would normally evoke a pupillary dilation (e.g., sexual events; Whipple, Ogden, & Komisaruk, 1992). One cannot suppress one's pupil response deliberately (Laeng, Sirois, & Gredebäck, 2012) and thus the pupil is a perfect candidate to examine involuntary emotion regulation processes.

Both cognitive load and emotional states have been shown to modulate pupillary responses. Specifically, both highly demanding tasks and highly arousing situations reduce light reflex, indicating reduced parasympathetic response, and increase dilation, indicating increased sympathetic activity (Bradley et al., 2008; Granholm, Asarnow, Sarkin, & Dykes, 1996; Kahneman & Beatty, 1966). For example, light reflex amplitude is reduced during anticipation of fear-provoking stimuli (Bitsios, Szabadi, & Bradshaw, 2004; Loewenfeld, 1993), and fear of shock (Bitsios, Szabadi, & Bradshaw, 1998). In addition, patients with anxiety disorders demonstrate a reduced light reflex compared to control participants (Bakes, Bradshaw, & Szabadi, 1990). Cognitive load was also found to reduce light reflex. Steinhauer, Condray, and Kasparek (2000) showed that the light reflex amplitude was smaller and latency was shorter (ended earlier) following a hard arithmetic task (subtract 7) compared to an easy arithmetic task (add 1). The authors suggested that increase in cognitive load leads to inhibition of the EWN via cortical projections.

Pupillary dilation, which indicates sympathetic activity, is also subjected to cognitive and emotional influences. Bradley et al. (2008) demonstrated that pupillary dilation for emotional pictures (positive and negative) is larger than pupillary dilation for neutral pictures and is correlated with SCR. Similarly, Partala and Surakka (2003) demonstrated increased pupil dilation for affective, compared to neutral, sounds. In addition, several studies indicated that depressed individuals and individuals at risk for depression showed sustained pupil dilation for negative words (Siegle, Granholm, Ingram, & Matt, 2001; Siegle, Steinhauer, Carter, Ramel, & Thase, 2003; Steidtmann, Ingram, & Siegle, 2010). Cognitive load (Beatty, 1982; Beatty & Lucero-Wagoner, 2000; Steinhauer et al., 2000) and tasks that recruit executive control (Brown et al., 1999; Laeng, Ørbo, Holmlund, & Miozzo, 2011; Siegle, Ichikawa, & Steinhauer, 2008; Siegle, Steinhauer, & Thase, 2004; van Steenbergen & Band, 2013) were also found to increase pupil dilation.

In the current study, we were interested in pupillary reactions to executive and emotional stimulation. More importantly, we explored whether executive control modulates emotion-related physiological responses, and whether this modulation affects both the sympathetic (i.e., pupillary dilation) and the parasympathetic (i.e., pupillary light reflex) systems. Participants were presented with a negative, neutral, or scrambled picture (Experiment 1) or with a negative or neutral sound (Experiment 2) that was preceded by a flanker stimulus. They were requested to respond to the direction of a central arrow (target) and ignore flanking arrows in close proximity. The target and the flankers could point to the same direction (congruent stimulus) or opposite directions (incongruent stimulus).

We expected to replicate previous findings showing increased pupil dilation (Brown et al., 1999; Laeng et al., 2011; Siegle et al., 2008; Siegle et al., 2004; van Steenbergen & Band, 2013) and decreased pupillary light reflex (e.g., Steinhauer et al., 2000) for incongruent compared to congruent stimuli. We also expected to replicate previous findings showing increased pupil dilation (e.g., Bradley et al., 2008; Partala & Surakka, 2003) and decreased pupillary light reflex (e.g., Bitsios et al., 1996; Granholm et al., 1996; Loewenfeld, 1993) for negative compared to neutral stimuli. More importantly, based on recent behavioral findings showing reduced emotional reactions following executive control recruitment (for reviews see Cohen & Henik, 2012; Okon-Singer et al., 2013), we predicted that emotion-related physiological effects would be more pronounced following congruent, compared to incongruent flanker stimuli.

2. Experiment 1

2.1. Materials and methods

2.1.1. Participants

Twenty-three undergraduate students (16 females, mean age was 22.64 years, SD = 1.36) from Ben-Gurion University of the Negev participated in the experiment in return for course credit or monetary payment. The study was approved by the ethics committee of the Psychology department. All participants signed an informed consent form, mentioning the presence of unpleasant pictures, prior to their participation in the experiment. All participants had normal or corrected-to-normal vision and no reported history of attention deficit disorder.

2.1.2. Stimuli

2.1.2.1. Flanker stimuli. Flanker stimuli consisted of a line of five arrows, in which the middle arrow pointed in the same direction as the other arrows (congruent stimuli) or in a different direction from the other arrows (incongruent stimuli). Each arrow subtended a visual angle of 1.5° from a viewing distance of 57 cm. The arrows were separated by a distance of 0.5°. The color of the arrows was black and the background was silver (RGB: 192, 192, 192; mean luminance[1] = 191).

2.1.2.2. Picture stimuli. Sixty-four negative and 64 neutral pictures from the International Affective Pictures System (IAPS; Lang, Bradley, & Cuthbert, 2008) were used. Moreover, we included a scrambled version of all of these pictures (a total of 256 different pictures). Pictures were selected based on the IAPS arousal ratings (ranging from 1 = not arousing, to 9 = highly arousing) and valence ratings (ranging from 1 = very unhappy, to 9 = very happy). Negative pictures were selected to have high arousal and negative valence ratings (mean valence = 2.8, mean arousal = 5.7), and neutral pictures were selected to have neutral valence and low arousal ratings (mean valence = 5.0, mean arousal = 3.2). Pictures subtended a visual angle of 22.3° from a viewing distance of 57 cm,

[1] Luminance was calculated using the following equation: luminance = $0.299 \times R + 0.587 \times G + 0.114 \times B$.