



## Caffeine modulates attention network function

Tad T. Brunyé<sup>a,b,\*</sup>, Caroline R. Mahoney<sup>a,b</sup>, Harris R. Lieberman<sup>c</sup>, Holly A. Taylor<sup>b</sup>

<sup>a</sup> US Army Natick Soldier Research, Development and Engineering Center, United States

<sup>b</sup> Tufts University, Department of Psychology, United States

<sup>c</sup> US Army Research Institute of Environmental Medicine, United States

### ARTICLE INFO

#### Article history:

Accepted 31 July 2009

Available online 5 September 2009

#### Keywords:

Caffeine  
Arousal  
Attention networks  
Visuospatial attention

### ABSTRACT

The present work investigated the effects of caffeine (0 mg, 100 mg, 200 mg, 400 mg) on a flanker task designed to test Posner's three visual attention network functions: alerting, orienting, and executive control [Posner, M. I. (2004). *Cognitive neuroscience of attention*. New York, NY: Guilford Press]. In a placebo-controlled, double-blind study using a repeated-measures design, we found that the effects of caffeine on visual attention vary as a function of dose and the attention network under examination. Caffeine improved alerting and executive control function in a dose–response manner, asymptoting at 200 mg; this effect is congruent with caffeine's adenosine-mediated effects on dopamine-rich areas of brain, and the involvement of these areas in alerting and the executive control of visual attention. Higher doses of caffeine also led to a marginally less efficient allocation of visual attention towards cued regions during task performance (i.e., orienting). Taken together, results of this study demonstrate that caffeine has differential effects on visual attention networks as a function of dose, and such effects have implications for hypothesized interactions of caffeine, adenosine and dopamine in brain areas mediating visual attention.

Published by Elsevier Inc.

### 1. Introduction

Caffeine (1,3,7-trimethylxanthine) is the most widely consumed psychoactive stimulant in the world, found naturally in many foods and beverages, and often cited for its positive effects on vigilance and mental alertness (for reviews, see IOM, 2001; Koelega, 1993; Lieberman, 1992, 2001; Smith, 2002; Snel, Lorist, & Tiegies, 2004; Spiller, 1997). Improvements in these processes have been commonly attributed to caffeine's antagonistic role at adenosine A<sub>1</sub> and A<sub>2A</sub> receptors in dopamine-rich brain areas, ultimately stimulating dopaminergic activity and resulting in increased wakefulness and pronounced motor activity (i.e., Garrett & Griffiths, 1997; Popoli, Reggio, Pezzola, Fuxe, & Ferré, 1998; Solinas et al., 2002). Indeed, many studies have demonstrated that caffeine reduces response times and error rates in tasks such as simple reaction time (Wesensten, Killgore, & Balkin, 2005), choice reaction time (Kenemans & Lorist, 1995; Lieberman, Tharion, Shukitt-Hale, Speckman, & Tulley, 2002), and visual vigilance (Fine et al., 1994; Lieberman et al., 2002). Further work suggests that caffeine may have positive influences on relatively higher-order processes such as visual selective attention (Kenemans, Weileman, Zeegers, & Verbaten, 1999; Lorist & Snel, 1997; Lorist, Snel, Kok, & Mulder, 1996; Ruijter, DeRuiter, & Snel, 2000), task switching

(Tiegies, Snel, Kok, Plat, & Ridderinkhof, 2007; Tiegies et al., 2006), conflict monitoring (Tiegies, Ridderinkhof, Snel, & Kok, 2004), and response inhibition (Barry et al., 2007).

Other work, however, suggests that whereas caffeine may improve overall processing speed on tasks requiring higher-order function, these improvements cannot be attributed to specific effects on response inhibition or selective visual attention (Kenemans & Verbaten, 1998; Lorist & Snel, 1997; Tiegies, Snel, Kok, & Ridderinkhof, 2009). To further elucidate the locus of caffeine effects on lower- versus higher-level visual attention, we examined whether caffeine differentially affects the function of three visual attention networks in a dose–response paradigm. Specifically, we used the Attention Network Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002), which is a modified flanker task that allows examination of the relative functioning of alerting, orienting and executive control networks (i.e., Posner, 1990) in a single unitary visual attention task. Our intention was to examine whether caffeine consumption ranging from 0 mg to 400 mg differentially affects lower- versus higher-order attention network functioning, and how these effects might be modulated by dose.

#### 1.1. Caffeine: psychopharmacology and physiology

Caffeine is a psychoactive stimulant that is abundantly available in both natural (e.g., coffee, tea, chocolate) and supplemented (e.g., soft drinks, energy bars) food and beverages, as well as over-the-counter remedies for migraines, colds, and fatigue (Gilbert,

\* Corresponding author. Address: Tufts University, Department of Psychology, 490 Boston Ave., Medford, MA 02155, United States.

E-mail address: [tbrunyo1@tufts.edu](mailto:tbrunyo1@tufts.edu) (T.T. Brunyé).

Marshman, Schweider, & Berg, 1976; James, 1991). Some studies estimate that over 80% of US adults and children habitually consume moderate daily amounts of caffeine (estimates range from 193–280 mg/day average; Barone & Roberts, 1996; Frary, Johnson, & Wang, 2005), likely due to its properties as a mild psychostimulant (Childs & de Wit, 2006). Peak plasma concentrations of caffeine occur in as few as 15 min and on average approximately 45 min after ingestion (Arnaud, 1987; Smith, 2002). A number of studies suggest that the most behaviorally-relevant role of caffeine is in blocking the inhibitory properties of endogenous adenosine (particularly at  $A_1$  and  $A_{2A}$  receptors), resulting in increased dopamine, norepinephrine and glutamate release (e.g., Ferre, Fredholm, Morelli, Popoli, & Fuxe, 1997; Fredholm, Arslan, Johansson, Kull, & Svenningsson, 1997; Smits, Boekema, DeAbreu, Thien, & van't Laar, 1987). The effects of caffeine on physiological functions are thought to result from interactions with both adenosine and phosphodiesterase, resulting in cardiostimulatory and antiasthmatic actions (Davis et al., 2003; IOM, 2001). The result of higher dopamine and glutamate concentrations, coupled with phosphodiesterase inhibition, is a net increase in central nervous system and cardiovascular activity. In addition to affecting cognitive performance, caffeine increases perception of alertness and wakefulness (Leatherwood & Pollet, 1982; Rusted, 1999) and sometimes anxiety (particularly at high doses; Lieberman, 1992; Loke, Hinrichs, & Ghoneim, 1985; Sicard et al., 1996).

### 1.2. Caffeine: behavior and cognition

Presumably as a direct result of altered CNS activity, caffeine appears to result in performance improvements on a variety of basic psychomotor tasks. For instance, performance on simple and choice reaction time tasks is faster and accuracy improves as a function of increasing doses (Kenemans & Lorist, 1995; Lieberman, Wurtman, Emde, Roberts, & Coviella, 1987; Lieberman et al., 2002; Wesensten et al., 2005); other work suggests that these advantages diminish with very high doses of caffeine (e.g., 600 mg; Roache & Griffiths, 1987). Extended vigilance is also generally improved following caffeine consumption (Frewer & Lader, 1991; Lieberman, Wurtman, Emde, Roberts, & Coviella, 1987; Mitchell & Redman, 1992). More recently, research has begun to examine the mechanisms responsible for these performance advantages. Lorist and Snel (1997) found that caffeine reduces stimulus evaluation times as reflected in the timing of electroencephalography (EEG) components (see also Lorist, Snel, Kok, & Mulder, 1996). Further work suggests that caffeine can shorten motor readiness potentials as measured by EEG during ergometer exercise (Barthel et al., 2001). Basic psychomotor tasks thus appear to be improved by more efficient stimulus feature analysis (i.e., Treisman & Gelade, 1980) and shorter-duration readiness potentials, leading to decreased overall response times; these effects also appear to be generally greater at higher doses.

More recently, research has identified some higher-order cognitive processes that caffeine appears to affect. In general, higher-order processes are those considered to be involved in the active monitoring, guidance, and coordination of behavior (Miller & Cohen, 2001). Tieges and colleagues have recently demonstrated that caffeine can reduce response time costs during task switching (Tieges et al., 2006; Tieges, Snel, Kok, Plat, & Ridderinkhof, 2007), and strengthen action monitoring (Tieges, Ridderinkhof, Snel, & Kok, 2004). Another component of higher-order cognitive function is inhibitory control, generally defined as the ability to inhibit inappropriate impulses and actions, and reduce the influence of interfering (and often action-incompatible) information (Shallice & Burgess, 1993). Work investigating inhibitory control suggests that caffeine can reduce interference costs during selective visual attention tasks (Lorist, Snel, Kok, & Mulder, 1994; Lorist et al.,

1996) and the Stroop color-word task (Hasenfratz & Battig, 1992; Kenemans, Weileman, Zeegers, & Verbaten, 1999; but for contradictory results, see Foreman, Barraclough, Moore, Mehta, & Madon, 1989). Other work, however, suggests that caffeine (in a 3 mg/kg dose) does not significantly reduce interference on a variety of inhibitory tasks, including a cued go/no-go paradigm, a stop-signal task, and a flanker task (Kenemans & Verbaten, 1998; Tieges, Snel, Kok, & Ridderinkhof, 2009). Thus, results are mixed with regard to caffeine's effects on higher-order control processes.

Several methodological characteristics might account for such contradictory results. First, as noted by Tieges et al. (2009), the caffeine doses used in previous work may not have been large enough to elicit effects on inhibitory control (p. 325). Indeed a dose approximating 200 mg may not be sufficiently high to produce changes in individuals who habitually drink 2–4 cups of coffee per day (i.e., 170–340 mg) (i.e., Kenemans & Verbaten, 1998; Tieges et al., 2009). Further, habitual coffee drinkers may be affected by both withdrawal effects and caffeine response (see James, 1994; Juliano & Griffiths, 2004), and the use of a predominantly female sample (89% female; Tieges et al., 2009) in the flanker task may limit the chances of finding caffeine effects on cognitive performance (i.e., females may be less prone to the effects of caffeine on cognitive performance; Gupta & Gupta, 1999).

As noted by Tieges et al. (2009), there is convincing evidence, however, to expect that caffeine might modulate the inhibitory control of attention, particularly on visual selective attention tasks. First, some research has demonstrated that caffeine improves conflict resolution in the classic Stroop task, which involves resolving a visual conflict between a word name and its color (i.e., Hasenfratz & Battig, 1992; Kenemans et al., 1999). Second, meta-analyses of brain activation during the Stroop task reveal a network including the anterior cingulate cortex and a number of regions in the prefrontal cortex (Bush, Luu, & Posner, 2000; Bush et al., 1998); similar results are found with performance monitoring and conflict resolution during flanker tasks, most often implicating the anterior cingulate cortex (ACC; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Casey et al., 2000; Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Mac Donald, Cohen, Stenger, & Carter, 2000). Given fMRI evidence that the ACC is up-regulated by caffeine, one might expect facilitation of conflict resolution either in the form of reduced response times or reduced error rates during flanker tasks (Koppelstaetter et al., 2008).

In support of this position, it should be noted that the ACC has dense dopaminergic innervation (Lumme, Aalto, Ilonen, Nägren, & Hietala, 2007) and dopamine binding in this region drives executive function (Ko et al., 2009). These findings suggest a potential role of increased dopamine availability as a result of caffeine consumption in brain regions mediating executive control, and that the result of such a process may be enhanced monitoring and conflict resolution.

### 1.3. The present study

To further examine the locus of caffeine's effects on lower- and higher-order visual attention, we conducted a double-blind, within-participant repeated-measures design with four levels of our treatment variable (0 mg, 100 mg, 200 mg, 400 mg caffeine). We assessed how caffeine affects visual attention in non-habitual consumers by using the Attention Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002). The ANT simultaneously tests the individual performance of the three networks in Posner's (1990) attention model by combining cued reaction time (Posner, 1980) and flanker tasks (Eriksen & Eriksen, 1974). Posner's three attention networks involve alerting, orienting, and executive attention.

The *alerting* network allows an individual to achieve and maintain a state of alertness during task performance by using predictive cues about trial onset. Alerting cues have been found to activate the thalamus and right and left frontal and parietal brain regions, similar to results found with vigilance and sustained attention tasks (Coull, Frith, Frackowiak, & Grasby, 1996; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Marrocco & Davidson, 1998; Posner & Petersen, 1990). Given the dense dopaminergic innervation of the human thalamus and prefrontal cortex (García-Cabezas, Rico, Sánchez-González, & Cavada, 2007; Sawaguchi & Goldman-Rakic, 1991, 1994; Sánchez-González, García-Cabezas, Rico, & Cavada, 2005; Williams & Goldman-Rakic, 1995), and that caffeine is generally found to improve simple reaction times on several simple psychomotor tasks, we expected similar effects in a positive dose–response relationship. Specifically, we expect that the advantage of cued versus non-cued trials in the ANT would increase as a function of higher caffeine dose.

The *orienting* network allows an individual to selectively attend to regions of space by directing attention to cued areas. Orienting attention (either covertly or overtly) towards particular regions of space has been found to activate the superior parietal lobe (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005). No work to date has specifically investigated caffeine's effects on the orienting function of visual attention. However, we hypothesize that given work demonstrating relatively sparse dopaminergic innervations of the parietal lobes, the orienting network may not be specifically affected by caffeine consumption (i.e., Lidow, Goldman-Rakic, Rakic, & Innis, 1989; Tassin et al., 1978). As such, we do not expect that caffeine will differentially affect people's ability to take advantage of spatial cues that orient them towards particular areas of space.

The *executive attention* network allows an individual to resolve a conflict among potential responses to a presented stimulus. As with the Stroop task, resolving conflict during the flanker task generally activates the anterior cingulate and lateral prefrontal cortices (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Bush, Luu, & Posner, 2000; Casey et al., 2000; Fan et al., 2005; Mac Donald, Cohen, Stenger, & Carter, 2000). Given the dense dopaminergic innervation of these areas (as reviewed above), and that caffeine could reasonably be expected to enhance the executive control of attention, we expect caffeine may modulate executive control by improving conflict resolution during flanker tasks, particularly with higher doses of caffeine. This hypothesis does not run specifically counter to the results of Tiegues et al. (2009); indeed it is possible that lower doses may not produce significant effects on conflict resolution. We do expect, however, that a higher dose (i.e., 400 mg) may enhance performance. Specifically, higher doses of caffeine may diminish the cost of presenting action-incompatible relative to action-compatible flankers in the ANT.

## 2. Method

### 2.1. Participants

Thirty-six Tufts University undergraduate students (16 male, 20 female; mean age 19.08; mean BMI 23.15) participated for monetary compensation (\$10 USD/h). All participants reported being low caffeine consumers ( $M = 42.5$  mg/day), non-smokers, in good health, not using prescription medication other than oral contraceptives, and not using nicotine in any form. Written informed consent was obtained, and all procedures were jointly approved by the Tufts University Institutional Review Board and the Human Use Review Committee of the U.S. Army Research Institute for Environmental Medicine.

### 2.2. Design

We used a double-blind, repeated-measures design with four levels of our independent variable, treatment (0 mg, 100 mg, 200 mg, 400 mg caffeine). Our highest dose was chosen given its similarity to caffeine levels found in the 20 oz coffee at a major franchise coffee house (i.e., 420 mg). Treatment order was counter-balanced across participants using a Latin square. Each treatment dose was administered in an identical color, size, weight and shape capsule. Placebo capsules were filled with physiologically-inert microcrystalline cellulose powder, which was also used as filler material in the two lower-dose caffeine capsules. The caffeine was 99.8% pure anhydrous USP-grade powder. Participants were tested during morning sessions following a 12-h fast during which they were only to consume water. A 12-h fast is thought to be a sufficient wash-out period to attenuate the effects of earlier caffeine consumption, particularly given that we only tested low consumers, and that the mean plasma and elimination half-lives of caffeine are both approximately 5 h in healthy individuals (Culm-Merked, von Moltke, Harmatz, & Greenblat, 2005; IOM, 2001; Statland & Demas, 1980). To encourage fasting compliance we collected saliva samples upon arrival for each test session (not further analyzed herein; see also Tiegues et al., 2009). Participants were further instructed not to use any over-the-counter medications or herbal supplements for 24 h prior to testing.

### 2.3. Materials

#### 2.3.1. Self-reported mood state

Participants completed the Brief Mood Introspection Scale (BMIS; Mayer & Gaschke, 1988) upon arrival to each test session and immediately prior to ANT administration.

#### 2.3.2. Attention network test

The ANT involves viewing a sequence of visual cues and arrows and responding to the direction of a central arrow. A cue can alert an individual that a trial is about to be presented only, or it can also orient the individual to a particular region of space (above or below fixation). A central target arrow is then presented within an array of congruent (same facing direction), incongruent (opposite facing direction), or neutral (no facing direction) flankers. Response time and accuracy are measured when the participant responds to the direction (left or right) of the central arrow. Three primary indicators of attentional function are calculated from the ANT data; first, one can compute the extent to which cues are *alerting* the participant of an upcoming trial, relative to when no-cue is provided (i.e., alerting network function). Second, one can compute the extent to which spatially-determinate cues are *orienting* the participant towards a particular region of the screen, relative to spatially-indeterminant cues (i.e., orienting network function). Finally, one can compute the extent to which incongruent relative to congruent or neutral flankers interfere with the determination of and response to a central arrow's facing direction (i.e., *executive control* network function). Behavioral, neuropsychological, and neuro-imaging evidence support the validity and reliability of the ANT as well as the notion of three independent attentional networks (i.e., Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Fan, Fossella, Sommer, Wu, & Posner, 2003; Neuhaus et al., 2007; Posner & Rothbart, 2005).

The ANT presents an easily-implemented and time-efficient method for measuring the separable contributions of the three attentional networks toward task performance. The test involves three blocks of 96 trials (total of 288 trials) presented in random order. Each block presents two trials for each of the four cue conditions (none, center, double, spatial), two target locations (top, bottom), two target directions (left, right), and three flanker conditions (neutral, congruent, incongruent). On each trial, the

participants identify and respond to the center arrow's facing direction (left or right). For a more complete description of the task and its parameters, refer to (Fan et al., 2002).

#### 2.4. Procedure

Participants completed six sessions: one intake session, one practice session during which participants were told to consume their normal caffeine amounts, and four test sessions corresponding to each treatment level. During the intake session, participants were fully screened and completed the informed consent. During the practice session, participants completed the BMIS, provided 6 ml saliva samples (not further analyzed here), and then practiced the complete ANT; they received full instructions on how to perform the task and had the opportunity to ask questions during two 3-min breaks (one following each block of 96 trials). Participants were told to respond to the center arrow's facing direction as quickly and accurately as possible; they were also told that on some trials they would receive an indication of when the trial was about to begin and/or where the trial would appear.

The practice and test sessions always took place in the morning at consistent times within participants, and each session was separated by at least three days. Test sessions were similar to the practice day with the exception of capsule consumption and a digestion period. During test sessions, participants completed the BMIS upon arrival, provided 6 ml saliva samples, and then consumed their assigned treatment capsule along with a cup of water. They then took a 30-min break; we chose this period of time in consideration of research showing that caffeine peak plasma concentrations vary widely and occur between 15 and 120 min after consumption (Arnaud, 1987; IOM, 2001). Following the break, participants again completed the BMIS and then began the ANT. Participants received two 3-min breaks during the ANT, and were tested in groups of up to 5 participants (each with an isolated workstation).

### 3. Results

#### 3.1. Self-reported mood state

Table 1 details adjective ratings as a function of treatment. Repeated-measures analyses of variance (ANOVA) on adjective ratings following caffeine consumption confirmed the effectiveness of our treatment manipulation. Overall, there were significant increases in participants' ratings of how *Lively*, *Peppy*, and *Jittery* they felt as a function of treatment level; conversely, there were also significant decreases in participants' ratings of how *Drowsy*, *Tired*, and *Calm* they felt as a function of treatment level. For adjectives with significant ANOVA results, Table 1 also lists Bonferroni-corrected ( $\alpha = .017$ ) *t*-test results, comparing each treatment level to 0 mg placebo.

#### 3.2. Attention network test

##### 3.2.1. Replication of original ANT results

First, we conducted two 4 (Cue Type: none, center, double, spatial)  $\times$  3 (Flanker Type: neutral, congruent, incongruent) repeated-measures ANOVAs in the 0 mg condition, one on RT and one on accuracy data. These tests were designed to confirm replication of the original ANT results (i.e., Fan et al., 2002). Response time data replicated earlier results, with a main effect of Cue Type,  $F(3, 147) = 36.62$ ,  $p < .01$ , and Flanker Type,  $F(2, 98) = 19.75$ ,  $p < .01$ , and an interaction between these two variables,  $F(6, 294) = 2.54$ ,  $p < .05$ . Overall, incongruent flankers increased response times relative to congruent or neutral flankers, and this effect was greatest when participants were given spatially indeterminate (center or

**Table 1**  
BMIS adjective ratings as a function of treatment dosage.

Adjective	Treatment							
	0 mg		100 mg		200 mg		400 mg	
	M	SD	M	SD	M	SD	M	SD
Lively <sup>++</sup>	2.33	.72	2.57	.87	2.75*	.69	3.00*	.83
Happy <sup>ns</sup>	2.72	.70	2.78	.86	2.86	.87	2.78	.94
Sad <sup>ns</sup>	1.89	.67	1.72	.78	1.67	.72	1.78	.80
Tired <sup>m</sup>	2.94	.71	2.72	.85	2.67	.79	2.50	.74
Caring <sup>ns</sup>	2.78	.68	2.72	.81	2.64	.80	2.58	.91
Content <sup>ns</sup>	2.94	.71	2.97	.74	2.86	.83	2.75	.81
Gloomy <sup>ns</sup>	1.58	.65	1.53	.65	1.72	.74	1.61	.69
Jittery <sup>++</sup>	1.69	.62	1.72	.81	2.08*	.94	2.52*	1.05
Drowsy <sup>++</sup>	2.61	.87	2.28	.88	2.53	.88	2.06*	.75
Grouchy <sup>ns</sup>	1.78	.83	1.67	.68	1.67	.79	1.67	.72
Peppy <sup>++</sup>	1.83	.74	2.06	.89	2.19*	.92	2.25*	.77
Nervous <sup>ns</sup>	1.92	.81	1.78	.68	1.89	.89	1.97	.94
Calm <sup>+</sup>	2.94	.71	2.97	.65	2.69	.79	2.56	.97
Loving <sup>ns</sup>	2.61	.80	2.72	.70	2.53	.88	2.47	.88
Fed up <sup>ns</sup>	1.92	.81	1.72	.70	1.75	.77	1.78	.76
Active <sup>ns</sup>	2.28	.85	2.61	.87	2.39	.90	2.52	.84

\*  $p < .05$ .

\*\*  $p < .01$ .

<sup>m</sup>  $p < .10$ .

<sup>ns</sup> Non-significant in ANOVA.

\* Significant Bonferroni-corrected ( $\alpha = .017$ ) *t*-test, comparing treatment level to 0 mg placebo.

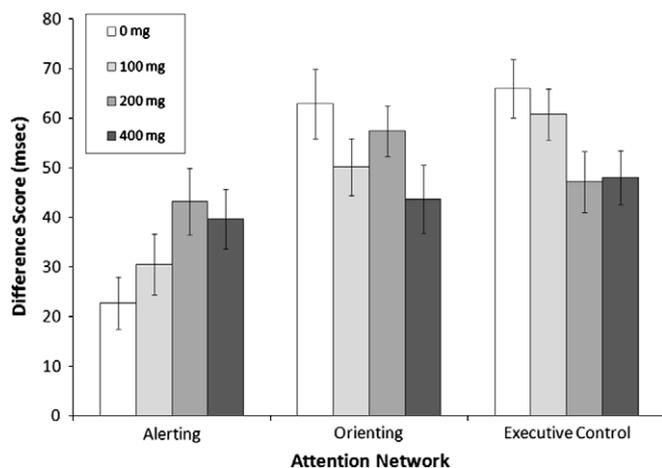
double) relative to spatial determinate (top/bottom) cues. Accuracy data further replicated earlier results, with a marginal main effect of Flanker Type,  $F(2, 66) = 2.35$ ,  $p < .10$ , suggesting that incongruent flankers showed lower accuracy relative to neutral and congruent flankers.

##### 3.2.2. Omnibus assessment of treatment effects

Second, we conducted two omnibus 4 (Cue Type: none, center, double, spatial)  $\times$  3 (Flanker Type: neutral, congruent, incongruent)  $\times$  4 (treatment: 0 mg, 100 mg, 200 mg, 400 mg) repeated-measures ANOVAs, one on RT and one on accuracy data. These analyses were designed to test whether treatment level differentially affected performance on the ANT test. Response time data analysis showed a main effect of treatment,  $F(3, 147) = 17.7$ ,  $p < .01$  (overall RTs: 0 mg,  $M = 523.43$ ,  $SE = 16.28$ ; 100 mg,  $M = 500.82$ ,  $SE = 13.41$ ; 200 mg,  $M = 496.38$ ,  $SE = 14.23$ ; 400 mg,  $M = 489.97$ ,  $SE = 14.32$ ), and that treatment interacted with Cue Type,  $F(9, 441) = 2.29$ ,  $p < .05$ , and marginally with Flanker Type,  $F(6, 294) = 2.05$ ,  $p < .10$ . Accuracy data did not reveal any main or interactive effects of treatment and thus will not be further analyzed.

##### 3.2.3. Treatment effects on attention networks

Third, we calculated difference scores for each of the three attention networks: alerting, orienting, and executive control. Difference scores allow for the independent assessment of each attention network (i.e., Fan et al., 2002, 2005; Redick & Engle, 2006), and are calculated as follows. The alerting difference score was calculated by subtracting average double-cue RTs from the no-cue RTs; higher difference scores thus indicate more efficient functioning of the alerting system. The orienting difference score was calculated by subtracting average spatial cue RTs from center cue RTs; higher difference scores thus indicate more efficient functioning of the orienting system. Finally, a conflict difference score was calculated by subtracting average congruent flanker RTs (across all cue types) from incongruent flanker RTs; lower difference scores thus indicate more efficient functioning of the conflict (executive control) system. Fig. 1 depicts difference scores for each of the three attention networks and four treatment levels.



**Fig. 1.** Mean difference scores and standard errors for each of the three attention networks and four treatment levels. Note that higher difference scores in the alerting and orienting networks indicate greater performance; conversely, lower difference scores in the executive control network indicate greater performance.

We then conducted three single-factor repeated-measures ANOVAs with four levels of the treatment variable (0 mg, 100 mg, 200 mg, 400 mg), one for each attention network difference score (see Fig. 1). Analysis of alerting difference scores demonstrated an effect of treatment,  $F(3, 105) = 2.99$ ,  $p < .05$ . Planned comparisons revealed lower alerting difference scores in the 0 mg condition relative to both the 200 mg,  $t(35) = 3.35$ ,  $p < .01$ , and 400 mg,  $t(35) = 2.58$ ,  $p < .02$ , conditions (all other comparisons  $p > .05$ ). In general, higher doses of caffeine led to enhanced alerting system function; this effect, however, appears to asymptote at 200 mg. Analysis of orienting difference scores demonstrated a marginal effect of treatment,  $F(3, 105) = 2.5$ ,  $p = .06$ . Planned comparisons revealed higher orienting difference scores in the 0 mg condition relative to the 400 mg condition,  $t(35) = 2.3$ ,  $p < .05$  (all other comparisons  $p > .05$ ). Interestingly, higher doses of caffeine led to diminished orienting system function, only becoming significant at the highest dose. Analysis of the conflict difference scores also demonstrated an effect of treatment,  $F(3, 105) = 3.30$ ,  $p < .05$ . Planned comparisons revealed higher conflict difference scores in the 0 mg condition relative to both the 200 mg,  $t(35) = 2.28$ ,  $p < .05$ , and 400 mg,  $t(35) = 2.32$ ,  $p < .05$ , conditions (all other comparisons  $p > .05$ ). In general, higher doses of caffeine led to enhanced executive control of attention; as with alerting, however, this effect appears to asymptote at 200 mg.

#### 3.2.4. Testing for withdrawal effects

To confirm that our results cannot be attributed to withdrawal effects, we conducted three  $t$ -tests comparing the practice day to the 0 mg day, one for each of the three attention network difference scores. Recall that participants were instructed to consume normal daily caffeine amounts on the practice day. No differences were revealed when comparing alerting scores,  $t(33) = .31$ ,  $p > .05$ , orienting scores,  $t(33) = .06$ ,  $p > .05$ , or executive control scores,  $t(33) = -.11$ ,  $p > .05$ , across the two sessions.

## 4. Discussion

The present study examined the effect of four caffeine doses on lower- and higher-level visual attention networks as defined by Posner's (1990) model and assessed with the attention network test. This test independently assesses the function of the alerting, orienting, and executive control networks. Caffeine differentially modulated visual attention as a function of both treatment dose

and network function assessed. In general, higher doses of caffeine improve performance of the alerting and executive control networks, but slightly diminish orienting network performance. Below we outline our results and discuss implications as a function of attention network.

### 4.1. Alerting network

The alerting network is theorized to be responsible for maintaining an alert state throughout task performance (Fan et al., 2002, 2005; Posner, 1990, 2004). The ANT assesses alerting network function by evaluating whether participants can take advantage of cues that alert them to trial onset. The extent to which response times are speeded by such cues is a reliable indication of alerting network function (Fan et al., 2002, 2005). Consistent with caffeine's well-known effects on lower-level visual attention tasks, we found that 200 mg and 400 mg of caffeine can improve participants' ability to take advantage of alerting cues. This result adds to a growing body of literature demonstrating that caffeine can have positive influences on basic psychomotor tasks (Frewer & Lader, 1991; Kenemans & Lorist, 1995; Lieberman et al., 1987, 2002; Mitchell & Redman, 1992; Wesensten et al., 2005).

The alerting network (as assessed by the ANT) was recently found to recruit a distributed network of brain regions, primarily the thalamus and bilateral frontal and parietal brain regions (Fan et al., 2005). Given the dense dopaminergic innervation of the human thalamus and prefrontal cortex (García-Cabezas, Rico, Sánchez-González, & Cavada, 2007; Sawaguchi & Goldman-Rakic, 1991, 1994; Sánchez-González, García-Cabezas, Rico, & Cavada, 2005; Williams & Goldman-Rakic, 1995), and that caffeine is generally thought to up-regulate dopaminergic availability (Ferre, Fredholm, Morelli, Popoli, & Fuxe, 1997; Fredholm, Arslan, Johansson, Kull, & Svenningsson, 1997; Smits, Boekema, DeAbreu, Thien, & van't Laar, 1987), the present results are consistent with the theorized effects of caffeine on CNS function. Further, we show that in non-habitual low caffeine consumers, the effects of 100 mg of caffeine on alerting function are negligible. Only with higher doses (200 mg or 400 mg) were we able to identify reliable effects of caffeine on this lower-level attention network.

### 4.2. Orienting network

Aptly named, the orienting network is theorized to be responsible for allowing individuals to selectively attend to particular regions of space and ultimately speed selecting and responding to visual stimuli (Fan et al., 2002, 2005; Posner, 1990, 2004). The ANT assesses orienting network function by determining whether participants can take advantage of cues that orient them towards upper and lower region of the screen, allowing them to better-prepare for upcoming trial location. The extent to which response times are speeded by upper or lower cues (relative to spatially-indeterminate cues) is a reliable indication of orienting network function (Fan et al., 2002, 2005). Until now, no research has examined how caffeine specifically affects the orienting network of visual attention. Presently, we found some evidence that high doses (400 mg) of caffeine can produce decrements in orienting network function, with participants less able to take advantage of spatially-determinate cues to focus visual attention in particular screen areas.

As noted in our hypotheses, we expected that caffeine would have little to no effect on orienting network function; this hypothesis was based on research demonstrating that orienting is primarily the locus of the parietal lobes (i.e., Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Fan et al., 2005), and some work showing rather sparse dopaminergic innervation of this brain region in humans and other animals (Lidow, Goldman-Rakic, Rakic, & Innis, 1989; Tassin et al., 1978). It is unclear why caffeine showed a

negative influence on orienting function. Some recent work in our laboratory, however, has demonstrated that high doses of caffeine (i.e., 400 mg) lead individuals to focus more on global rather than local elements of visual scenes (Mahoney et al., 2009); similar global focus effects have been shown at high levels of arousal (Brunyé, Mahoney, Augustyn, & Taylor, 2009; Corson & Verrier, 2007; Pesce, Tessitore, Casella, Pirritano, & Capranica, 2007). Given these results, one might expect that orienting visual attention to relatively local regions of space might be impaired at higher doses of caffeine. It is difficult to reconcile this explanation, however, with the executive control results; that is, if participants show relatively global visual attention biases at 400 mg of caffeine, they might also show difficulty inhibiting the influence of incompatible flankers (the present results show the opposite effect).

An alternative explanation for the reduced orienting scores is the possibility that such a pattern may indicate *improvement* in orienting function rather than a decrement, per se. This possibility has been put forth by Fan and Posner (2004) as well as Wang and Fan (2007), who suggest that at high levels of intrinsic orienting function, individuals may take less advantage of (or are less dependent upon) orienting cues. In light of the present results this rationale would suggest that caffeine may improve the intrinsic efficiency of the orienting network, which may appear (in a numerical sense) as reduced orienting scores on the ANT. This is an intriguing possibility. Given that the present effect on orienting function was only marginally significant, future research should attempt to replicate this effect and, if persistent, seek to identify its origins.

#### 4.3. Executive control network

The executive control network is theorized to be responsible for allowing individuals to inhibit action-incompatible visual information (i.e., conflict resolution), in this case the effects of incongruent relative to congruent or neutral flanker arrows (Fan et al., 2002, 2005; Posner, 1990, 2004). The ANT assesses executive control by evaluating whether participants can inhibit the effects of opposite-facing flankers while responding only to the direction of the center arrow, relative to trials when the flankers were congruent (and in some cases neutral; Fan et al., 2002). The extent to which performance is slowed by incongruent flankers demonstrates the inefficiency of executive control (Fan et al., 2002, 2005). Until now, results have been mixed with regard to the effects of caffeine on tasks demanding selective visual attention; indeed some have demonstrated improvement on these tasks (Lorist, Snel, Kok, & Mulder, 1994; Lorist et al., 1996) and others have identified no reliable effects (Kenemans & Verbaten, 1998; Tiegies et al., 2009). We show that low caffeine consumers exhibit dose-dependent increases in executive control function at doses exceeding those typically used in previous studies (i.e., 200 mg, 400 mg). The present findings underscore the importance of investigating caffeine effects on highly sensitive and unified tasks in a dose–response manner, particularly at doses exceeding an individual's ordinary consumption levels. We do note, however, that these doses are similar to those found in commonly-consumed beverages. For instance, 20 oz. coffees at a major franchised coffee houses often exceed 400 mg (McCusker, Goldberger, & Cone, 2003).

Tasks demanding the executive control of visual attention involve a number of prefrontal brain areas in concert with the anterior cingulate cortex (Botvinick et al., 2001; Bush et al., 1998, 2000; Casey et al., 2000; Fan, Flombaum, et al., 2003; Fan, Fossella, et al., 2003; Mac Donald et al., 2000). These same brain areas have been shown to be up-regulated by caffeine (e.g., Koppelstaetter et al., 2008), and dopamine has been identified as a critical neurotransmitter for a supporting executive function in these areas (e.g., Ko et al., 2009). The present findings support the role of caffeine in enhancing conflict resolution through the

interaction of dopaminergic pathways with anterior cingulate and prefrontal brain regions. It seems likely that advantages in executive control are only reliably seen with relatively high doses of caffeine in individuals with low-consumption profiles. These effects may be specific to reactive rather than active inhibition (i.e., Fillmore & Rush, 2002); whereas there is some converging evidence that reactive inhibition may be improved as a result of caffeine consumption (see also Hasenfratz & Battig, 1992; Kenemans et al., 1999; Lorist et al., 1994, 1996), no studies examining active inhibition have found such effects (e.g., on stop-signal tasks; Tiegies et al., 2009).

#### 5. Conclusions

Caffeine is an exceedingly common stimulant with diverse influences on central nervous system function. The present study assessed the effects of caffeine on both lower- and higher-level visual attention processes by using the attention network test. We found that caffeine improves participants' ability to efficiently use alerting cues and inhibit the influence of action-incompatible information. The former result is in accordance with several decades of research demonstrating that caffeine improves performance on tasks requiring sustained attention and vigilance (Fine et al., 1994; Kenemans & Lorist, 1995; Lieberman et al., 2002; Wesensten et al., 2005). The latter result supports some of the extant literature demonstrating beneficial effects of caffeine on executive control in general (Tiegies et al., 2006, 2007) and visual selective attention in particular (e.g., Lorist et al., 1994, 1996). This finding, however, contradicts other research demonstrating no effect of caffeine on visual selective attention (Kenemans & Verbaten, 1998; Tiegies et al., 2009).

There are few ways to reconcile these differences. Unlike previous studies, participants in the present study were not habitual caffeine consumers and thus may require lower doses to exhibit effects on the executive control of attention. Indeed 200 mg was sufficient to induce performance improvement during conflict resolution, and 400 mg did not improve this process beyond that effect. Such asymptotic effects of caffeine (i.e., Lieberman et al., 1987; Robelin & Rogers, 1998) on higher-order control processes have also been found when using 3 and 6 mg/kg caffeine (Tiegies et al., 2006, 2007). It could be the case that reaching asymptotic performance improvements occurs at lower doses in participants with lower consumption profiles. As such, some previous work may not have used a sufficiently high dose (3 mg/kg, Kenemans & Verbaten, 1998; Tiegies et al., 2009; 250 mg, Kenemans et al., 1999) to elicit effects amongst habitual consumers<sup>1</sup>. Dose–response manipulations make it possible to examine such possibilities in a range of consumption profiles; we suggest that future research examining caffeine effects on executive control of attention use similar designs.

Given the prevalence of caffeine consumption it is critical to understand its effects on the brain and associated cognitive processes. Our results add to a growing body of evidence showing that caffeine can have beneficial effects on attentional processes recruiting brain regions with dense dopaminergic innervation, such as the anterior cingulate cortex, thalamus, and prefrontal cortex (i.e., Coull, Frith, Frackowiak, & Grasby, 1996; Fan et al., 2005; Ferré et al., 1997; Fredholm et al., 1997; García-Cabezas et al., 2007; Hasenfratz & Battig, 1992; Kenemans et al., 1999; Koppelstaetter et al., 2008; Lorist et al., 1994, 1996; Sawaguchi & Goldman-Rakic, 1991, 1994; Smits, Boekema, DeAbreu, Thien, & van't Laar, 1987; Sánchez-González et al., 2005; Tiegies et al., 2006; Williams & Goldman-Rakic, 1995).

<sup>1</sup> In the present study, the low-consumer participants averaged 150 lbs in body weight, which approximates a 200 mg dose at 3 mg/kg.

## Acknowledgments

The opinions expressed herein are those of the authors and do not reflect those of the United States Army. We thank Jennifer Rourke and William Shirer for their careful assistance with data collection, scoring and manuscript preparation.

## References

- Arnaud, M. J. (1987). The pharmacology of caffeine. *Progress in Drug Research*, 31, 273–313.
- Barone, J. J., & Roberts, H. R. (1996). Caffeine consumption. *Food Chemistry and Toxicology*, 34, 119–129.
- Barry, R. J., Johnstone, S. J., Clarke, A. R., Rushby, J. A., Brown, C. R., & McKenzie, D. N. (2007). Caffeine effects on ERPs and performance in an auditory Go/NoGo task. *Clinical Neurophysiology*, 118, 2692–2699.
- Barthel, T., Mechau, D., Wehr, T., Schmittker, R., Liesen, H., & Weiss, M. (2001). Readiness potential in different states of physical activation and after ingestion of taurine and/or caffeine containing drinks. *Amino Acids*, 20, 63–73.
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, 108, 624–652.
- Brunyé, T. T., Mahoney, C. R., Augustyn, J. S., & Taylor, H. A. (2009). Emotional state and local versus global spatial memory. *Acta Psychologica*, 130, 138–146.
- Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Science*, 4, 215–222.
- Bush, G., Whalen, P. J., Rosen, B. R., Jenike, M. A., McInerney, S. C., & Rauch, S. L. (1998). The counting Stroop: An interference task specialized for functional neuroimaging-validation study with functional MRI. *Human Brain Mapping*, 6, 270–282.
- Casey, B. J., Thomas, M. L., Welsh, T. F., Badgaiyan, R. D., Eccard, C. H., Jennings, J. R., et al. (2000). Dissociation of response conflict, attentional selection, and expectancy with fMRI. *Proceedings of the National Academy of Sciences of the United States of America*, 97, 8728–8733.
- Childs, E., & de Wit, H. (2006). Subjective, behavioral, and physiological effects of caffeine in light, nondependent caffeine users. *Psychopharmacology*, 185, 514–523.
- Corbetta, M., Kincade, J. M., Ollinger, J. M., McAvoy, M. P., & Shulman, G. L. (2000). Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature Neuroscience*, 3, 292–297.
- Corson, Y., & Verrier, N. (2007). Emotions and false memories: Valence or arousal? *Psychological Science*, 18(3), 208–211.
- Coull, J. T., Frith, C. D., Frackowiak, R. S., & Grasby, P. M. (1996). A fronto-parietal network for rapid visual information processing: A PET study of sustained attention and working memory. *Neuropsychologia*, 34(11), 1085–1095.
- Culm-Merkel, K. E., von Moltke, L. L., Harmatz, J. S., & Greenblat, D. J. (2005). Fluvoxamine impairs single-dose caffeine clearance without altering caffeine pharmacodynamics. *British Journal of Clinical Pharmacology*, 60, 486–493.
- Davis, J. M., Zhao, Z., Stock, H. S., Mehl, K. A., Buggy, J., & Hand, G. A. (2003). Central nervous system effects of caffeine and adenosine on fatigue. *American Journal of Physiology – Regulatory, Integrative and Comparative Physiology*, 284, 399–404.
- Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a non-search task. *Perception and Psychophysics*, 16, 143–146.
- Fan, J., Flombaum, J. I., McCandliss, B. D., Thomas, K. M., & Posner, M. I. (2003). Cognitive and brain consequences of conflict. *Neuroimage*, 18, 42–57.
- Fan, J., Fossella, J. A., Sommer, T., Wu, Y., & Posner, M. I. (2003). Mapping the genetic variation of executive attention onto brain activity. *Proceedings of the National Academy of Sciences of the United States of America*, 100, 7406–7411.
- Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *Neuroimage*, 26, 471–479.
- Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, 14, 340–347.
- Fan, J., & Posner, M. I. (2004). Human attentional networks. *Psychiatrische Praxis*, 31(Suppl. 2), 210–214.
- Ferre, S., Fredholm, B. B., Morelli, M., Popoli, P., & Fuxe, K. (1997). Adenosine-dopamine receptor-receptor interactions as an integrative mechanism in the basal ganglia. *Trends in Neuroscience*, 20, 482–487.
- Fillmore, M. T., & Rush, C. R. (2002). Impaired inhibitory control of behavior in chronic cocaine users. *Drug and Alcohol Dependence*, 66, 265–273.
- Fine, B. J., Kobrick, J. L., Lieberman, H. R., Marlowe, B., Riley, R. H., & Tharion, W. J. (1994). Effects of caffeine or diphenhydramine on visual vigilance. *Psychopharmacology*, 114, 233–238.
- Foreman, N., Barraclough, S., Moore, C., Mehta, A., & Madon, M. (1989). High doses of caffeine impair performance of a numerical version of the Stroop task in men. *Pharmacology, Biochemistry, and Behavior*, 32, 399–403.
- Frary, C. D., Johnson, R. K., & Wang, M. Q. (2005). Food sources and intakes of caffeine in the diets of persons in the United States. *Journal of the American Dietetic Association*, 105, 110–113.
- Fredholm, B. B., Arslan, G., Johansson, B., Kull, B., & Svenningsson, P. (1997). Adenosine A2A receptors and the actions of caffeine. In Y. Okada (Ed.), *The role of adenosine in the nervous system* (pp. 51–74). Amsterdam: Elsevier Science.
- Frewer, L. J., & Lader, M. (1991). The effects of caffeine on two computerized tests of attention and vigilance. *Human Psychopharmacology*, 6, 119–128.
- García-Cabezas, M. A., Rico, B., Sánchez-González, M. A., & Cavada, C. (2007). Distribution of the dopamine innervation in the macaque and human thalamus. *Neuroimage*, 34, 965–984.
- Garrett, B. E., & Griffiths, R. R. (1997). The role of dopamine in the behavioral effects of caffeine in animals and humans. *Pharmacology, Biochemistry, and Behavior*, 57, 533–541.
- Gilbert, R. M., Marshman, J. A., Schweider, M., & Berg, R. (1976). Caffeine content of beverages as consumed. *Canadian Medical Association Journal*, 114, 205–208.
- Gupta, U., & Gupta, B. S. (1999). Caffeine, impulsivity, and performance. In B. S. Gupta & U. Gupta (Eds.), *Caffeine and behavior: Current views and research trends* (pp. 191–205). Washington, DC: CRC Press.
- Hasenfratz, M., & Battig, K. (1992). Action profiles of smoking and caffeine: Stroop effect, EEG and peripheral physiology. *Pharmacology, Biochemistry, and Behavior*, 42, 155–161.
- IOM (Institute of Medicine) (2001). *Committee on Military Nutrition Research, Food and Nutrition Board, Institute of Medicine. Caffeine for the sustenance of mental task performance: Formulations for military operations*. Washington, DC: National Academy Press.
- James, J. E. (1991). *Caffeine and health*. San Diego, CA: Academic Press.
- James, J. E. (1994). Does caffeine enhance or merely restore degraded psychomotor performance? *Neuropsychobiology*, 30, 124–125.
- Juliano, L. M., & Griffiths, R. R. (2004). A critical review of caffeine withdrawal: Empirical validation of symptoms and signs, incidence, severity, and associated features. *Psychopharmacology*, 176, 1–29.
- Kenemans, J. L., & Lorist, M. M. (1995). Caffeine and selective visual processing. *Pharmacology, Biochemistry, and Behavior*, 52, 461–471.
- Kenemans, J. L., & Verbaten, M. N. (1998). Caffeine and visuo-spatial attention. *Psychopharmacology*, 135, 353–360.
- Kenemans, J. L., Weileman, J. S., Zeegers, M., & Verbaten, M. N. (1999). Caffeine and stroop interference. *Pharmacology, Biochemistry, and Behavior*, 63, 589–598.
- Ko, J. H., Ptito, A., Monchi, O., Cho, S. S., Van Eimeren, T., Pellecchia, G., et al. (2009). Increased dopamine release in the right anterior cingulate cortex during the performance of a sorting task: A [11C]FLB 457 PET study. *Neuroimage*, 46, 516–521.
- Koelega, H. S. (1993). Stimulant drugs and vigilance performance: A review. *Psychopharmacology*, 111, 1–16.
- Koppelstaetter, F., Poeppel, T. D., Siedentopf, C. M., Ischebeck, A., Verius, M., Haala, I., et al. (2008). Does caffeine modulate verbal working memory processes? An fMRI study. *Neuroimage*, 39, 492–499.
- Leatherwood, P., & Pollet, P. (1982). Diet induced mood changes in normal populations. *Journal of Psychiatric Research*, 17, 147–154.
- Lidow, M. S., Goldman-Rakic, P. S., Rakic, P., & Innis, R. B. (1989). Dopamine D2 receptors in the cerebral cortex: Distribution and pharmacological characterization with [3H]raclopride. *Proceedings of the National Academy of Sciences*, 86, 6412–6416.
- Lieberman, H. R. (1992). Caffeine: Factors affecting human performance. In D. Jones & A. Smith (Eds.), *The physical environment* (Vol. II). London: Academic Press.
- Lieberman, H. R. (2001). The effects of ginseng, ephedrine, and caffeine on cognitive performance, mood, and energy. *Nutrition Reviews*, 59, 91–102.
- Lieberman, H. R., Tharion, W. J., Shukitt-Hale, B., Speckman, K. L., & Tulley, R. (2002). Effects of caffeine, sleep loss, and stress on cognitive performance and mood during U.S. Navy SEAL training. Sea-air land. *Psychopharmacology*, 164, 250–261.
- Lieberman, H. R., Wurtman, R. J., Emde, G. G., Roberts, C., & Coviella, I. L. G. (1987). The effects of low doses of caffeine on human performance and mood. *Psychopharmacology*, 92, 308–312.
- Loke, W. H., Hinrichs, J. V., & Ghoneim, M. M. (1985). Caffeine and diazepam: Separate and combined effects on mood, memory, and psychomotor performance. *Psychopharmacology*, 87, 344–350.
- Lorist, M. M., & Snel, J. (1997). Caffeine effects on perceptual and motor processes. *Electroencephalography and Clinical Neurophysiology*, 102, 401–413.
- Lorist, M. M., Snel, J., Kok, A., & Mulder, G. (1994). Influence of caffeine on selective attention in well-rested and fatigued subjects. *Psychophysiology*, 31, 525–534.
- Lorist, M. M., Snel, J., Kok, A., & Mulder, G. (1996). Acute effects of caffeine on selective attention and visual search processes. *Psychophysiology*, 33, 354–361.
- Lumme, V., Aalto, S., Ilonen, T., Nägren, K., & Hietala, J. (2007). Dopamine D2/D3 receptor binding in the anterior cingulate cortex and executive functioning. *Psychiatry Research: Neuroimaging*, 156, 69–74.
- Mac Donald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science*, 288, 1835–1838.
- Mahoney, C. R., Brunyé, T. T., Lieberman, H. R., Shirer, W., Augustyn, J. S., & Taylor, H. A. (2009). Physiological arousal facilitates global attentional focus. In *Poster presentation at the 2009 society for neuroscience conference*. Chicago, IL.
- Marrocco, R. T., & Davidson, M. C. (1998). Neurochemistry of attention. In R. Parasuraman (Ed.), *The attentive brain* (pp. 35–50). Cambridge, MA: Massachusetts Institute of Technology Press.
- Mayer, J. D., & Gaschke, Y. N. (1988). The experience and meta-experience of mood. *Journal of Personality and Social Psychology*, 55, 102–111.
- McCusker, R. R., Goldberger, B. A., & Cone, E. J. (2003). Caffeine content of specialty coffees. *Journal of Analytical Toxicology*, 27, 520–522.
- Miller, E., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, 24, 167–202.
- Mitchell, P. J., & Redman, J. R. (1992). Effects of caffeine, time of day and user history on study-related performance. *Psychopharmacology*, 109, 121–126.

- Neuhaus, A. H., Koehler, S., Opgen-Rhein, C., Urbanek, C., Hahn, E., & Dettling, M. (2007). Selective anterior cingulate cortex deficit during conflict solution in schizophrenia: An event-related potential study. *Journal of Psychiatric Research, 41*, 635–644.
- Pesce, C., Tessitore, A., Casella, R., Pirritano, M., & Capranica, L. (2007). Focusing on visual attention at rest and during physical exercise in soccer players. *Journal of Sports Sciences, 25*, 1259–1270.
- Popoli, P., Reggio, R., Pezzola, A., Fuxe, K., & Ferré, S. (1998). Adenosine A1 and A2A receptor antagonists stimulate motor activity: Evidence for an increased effectiveness in aged rats. *Neuroscience Letters, 251*, 201–204.
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3–25.
- Posner, M. I. (1990). Hierarchical distributed networks in the neuropsychology of selective attention. In A. Caramazza (Ed.), *Cognitive neuropsychology and neurolinguistics* (pp. 187–210). Hillsdale, NJ: Lawrence Erlbaum.
- Posner, M. I. (2004). *Cognitive neuroscience of attention*. New York, NY: Guilford Press.
- Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 1*, 25–42.
- Posner, M. I., & Rothbart, M. K. (2005). Influencing brain networks: Implications for education. *TRENDS in Cognitive Sciences, 9*, 99–103.
- Redick, T. S., & Engle, R. W. (2006). Working memory capacity and attention network test performance. *Applied Cognitive Psychology, 20*, 713–721.
- Roache, J. D., & Griffiths, R. R. (1987). Interactions of diazepam and caffeine: Behavioral and subjective dose effects in humans. *Pharmacology, Biochemistry, and Behavior, 26*, 801–812.
- Robelin, M., & Rogers, P. J. (1998). Mood and psychomotor performance effects of the first, but not of subsequent, cup-of-coffee equivalent doses of caffeine consumed after overnight caffeine abstinence. *Behavioral Pharmacology, 9*, 611–618.
- Ruijter, J., DeRuiter, M. B., & Snel, J. (2000). The effects of caffeine on visual selective attention to color: An ERP study. *Psychophysiology, 37*, 427–439.
- Rusted, J. (1999). Caffeine and cognitive performance: Effects on mood or mental processing. In B. S. Gupta & U. Gupta (Eds.), *Caffeine and behavior: Current views and research trends* (pp. 221–229). Washington, DC: CRC Press.
- Sánchez-González, M. A., García-Cabezas, M. A., Rico, B., & Cavada, C. (2005). The primate thalamus is a key target for brain dopamine. *Journal of Neuroscience, 25*, 6076–6083.
- Sawaguchi, T., & Goldman-Rakic, P. S. (1991). D1 dopamine receptors in prefrontal cortex: Involvement in working memory. *Science, 251*, 947–950.
- Sawaguchi, T., & Goldman-Rakic, P. S. (1994). The role of D1-dopamine receptors in working memory: Local injections of dopamine antagonists into the prefrontal cortex of rhesus monkeys performing an oculomotor delayed-response task. *Journal of Neurophysiology, 71*, 515–528.
- Shallice, T., & Burgess, P. W. (1993). Supervisory control of action and thought selection. In A. D. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awareness and control*. Oxford: Oxford University Press.
- Sicard, B. A., Perault, M. C., Enslin, M., Chauffard, F., Vandel, B., & Tachon, P. (1996). The effects of 600 mg of slow release caffeine on mood and alertness. *Aviation, Space, and Environmental Medicine, 67*, 859–862.
- Smith, A. (2002). Effects of caffeine on human behavior. *Food and Chemical Toxicology, 40*, 1243–1255.
- Smits, P., Boekema, P., DeAbreu, R., Thien, T., & van't Laar, A. (1987). Evidence for an antagonism between caffeine and adenosine in the human cardiovascular system. *Journal of Cardiovascular Pharmacology, 10*, 136–143.
- Snel, J., Lorist, M. M., & Tiegies, Z. (2004). In A. Nehlig (Ed.), *Coffee, caffeine, and cognitive performance*. Boca Raton, FL: CRC Press.
- Spiller, G. (Ed.). (1997). *Caffeine*. Boca Raton, FL: CRC Press.
- Solinas, M., Ferré, S., You, Z. B., Karcz-Kubicha, M., Popoli, P., & Goldberg, S. R. (2002). Caffeine induces dopamine and glutamate release in the shell of the nucleus accumbens. *Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 22*, 6321–6324.
- Statland, B. E., & Demas, T. J. (1980). Serum caffeine half-lives. Healthy subjects vs. patients having alcoholic hepatic disease. *American Journal of Clinical Pathology, 73*, 390–393.
- Tassin, J. P., Bockaert, J., Blanc, G., Stinus, L., Thierry, A. M., Lavielle, S., et al. (1978). Topographical distribution of dopaminergic innervation and dopaminergic receptors of the anterior cerebral cortex of the rat. *Brain Research, 154*, 241–251.
- Tiegies, Z., Ridderinkhof, K. R., Snel, J., & Kok, A. (2004). Caffeine strengthens action monitoring: Evidence from the error-related negativity. *Cognitive Brain Research, 21*, 87–93.
- Tiegies, Z., Snel, J., Kok, A., Plat, N., & Ridderinkhof, K. R. (2007). Effects of caffeine on anticipatory control processes: Evidence from a cued task-switch paradigm. *Psychophysiology, 44*, 561–578.
- Tiegies, Z., Snel, J., Kok, A., & Ridderinkhof, J. R. (2009). Caffeine does not modulate inhibitory control. *Brain and Cognition, 69*, 316–327.
- Tiegies, Z., Snel, J., Kok, A., Wijnen, J. G., Lorist, M., & Ridderinkhof, K. R. (2006). Caffeine improves anticipatory processes in task switching. *Biological Psychology, 73*, 101–113.
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12*, 97–136.
- Wang, H., & Fan, J. (2007). Human attentional networks: A connectionist model. *Journal of Cognitive Neuroscience, 19*, 1678–1689.
- Wesensten, N. J., Killgore, W. D. S., & Balkin, T. J. (2005). Performance and alertness effects of caffeine, dextroamphetamine, and modafinil during sleep deprivation. *Journal of Sleep Research, 14*, 255–266.
- Williams, G. V., & Goldman-Rakic, P. S. (1995). Modulation of memory fields by dopamine D1 receptors in prefrontal cortex. *Nature, 376*, 572–575.