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Caffeine Enhances Real-World Language Processing: Evidence from a Proofreading Task

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Abstract

Caffeine has become the most prevalently consumed psychostimulant in the world, but its influences on daily real-world functioning are relatively unknown. The present work investigated the effects of caffeine (0mg, 100mg, 200mg, 400mg) on a commonplace language task that required readers to identify and correct four error types in extended discourse: simple local errors (misspelling 1-2 syllable words), complex local errors (misspelling 3-5 syllable words), simple global errors (incorrect homophones), and complex global errors (incorrect subject-verb agreement, and verb tense). In two placebo-controlled, double-blind studies using repeated-measures designs, we found higher detection and repair rates for complex global errors, asymptoting at 200 mg in low consumers (Experiment 1) and peaking at 400 mg in high consumers (Experiment 2). In both cases, covariate analyses demonstrated that arousal state mediated the relationship between caffeine consumption and the detection and repair of complex global errors. Detection and repair rates for the other three error types were not affected by caffeine consumption. Taken together, we demonstrate that caffeine has differential effects on error detection and repair as a function of dose and error type, and this relationship is closely tied to caffeine's effects on subjective arousal state. These results support the notion that central nervous system stimulants may enhance global processing of language-based materials, and suggest that such effects may originate in caffeine-related right hemisphere brain processes. Implications for understanding the relationships between caffeine consumption and real-world cognitive functioning are discussed.

Keywords: caffeine, arousal, language, discourse cohesion

Caffeine Enhances Real-World Language Processing:

Evidence from a Proofreading Task

Language processing necessitates attention to a variety of discourse features: Comprehenders must attend to the meanings of words, the syntactic connections established between those ideas, the larger themes reflected by the coherence of clauses and sentences, and the pragmatic conveyances that color linguistic experience. Successful comprehension depends upon being able to manage these multiple levels of linguistic analysis, moving between the local concepts conveyed in a text or conversation, and generating inferences about the general ideas that speakers and authors hope will emerge from their productions. The ability to comprehend language involves interactions between multiple levels of analysis, including the local processing of lexical information, and the relatively global processing of pragmatic, sentence-level contextual and discourse-level information (e.g., Gernsbacher, 1994). This latter process is particularly crucial, as extracting a global message during reading or listening allows us to understand language at a level that goes beyond the individual words and clauses (e.g., Zwaan & Radvansky, 1998). Global meanings, including themes, morals, take-home messages, and the like are usually the intended products of linguistic productions. Of course, building global understandings and inferences is not entirely easy, as they require attention to multiple, potentially disparate sections of text (e.g., Gernsbacher, 1994; Graesser, Singer, & Trabasso, 1994). Additionally those global inferences occur only under specific conditions, such as when readers have global processing as a goal or texts encourage such processing (e.g., Albrecht, O'Brien, Mason, Myers, 1995; Brunyé & Taylor, 2008; McKoon & Ratcliff, 1992; Rapp & Mensink, in press; Zwaan & Rapp, 2006).

Because these conditions have been of particular interest to the field of language comprehension, researchers have investigated not only factors that encourage global processing, but also the cognitive and neural mechanisms that might underlie such activity. To date, brain imaging and lesion studies demonstrate that the right hemisphere plays a significant role in extracting global meaning from language, which appears to be involved in several relevant processes including inference generation, maintaining thematic meaning, and resolving pronominal references (e.g., Beeman, 1993, 2005; Brownell & Martino, 1998; St George, Kutas, Martinez, & Sereno, 1999). Factors that motivate right hemisphere activity might therefore prove influential for increasing global processing. Previous research has demonstrated that arousal broadly up-regulates right hemisphere activity (e.g., Lorist & Snel, 1997; Nitschke, Heller, & Miller, 2000), perhaps via serotonergic and dopaminergic pathways in a right frontoparietal brain network thought critical for active cognitive control (Davidson, Horvitz, Tottenham, Fossella, Watts, Ulug, & Casey, 2004; Fan, Fossella, Sommer, Wu, & Posner, 2003; Smith, Taylor, Brammer, Toone, & Rubia, 2006; Fassbender, Simoes-Franklin, Murphy, Hester, Meaney, Robertson, & Garavan, 2006). The present experiments were designed to test whether increasing arousal levels, via caffeine administration, would produce concomitant increases in global language processing. To this end, we examined whether individuals would differentially notice global or local errors (one obvious marker of text processing) as a function of increased arousal. We specifically tested this hypothesis by administering four caffeine doses (0, 100, 200 and 400 mg) in a repeated-measures design and measuring their influence on participants' ability to detect and repair local- versus global-level errors while proofreading an extended discourse. We predicted that caffeine intake would improve global-level relative to local-level error detection and repair, and that this difference would be influenced by the amount of caffeine consumed. In addition, because of individuals' differential intake of caffeine during their everyday activities, we investigated whether any obtained effects could also be distinguished as a function of consumption habits.

Below we briefly review the extant literatures on hemispheric influences on local and global processing, as well as on the role of caffeine-based arousal on the right hemisphere, as a means of elucidating the motivations for the project and the supporting research for the project's predictions.

Local and Global Language Processing in the Brain

Seminal theories of language organization have generally implicated the left hemisphere in both language comprehension and production, based largely on research investigating language abnormalities in aphasic patients (Wernicke, 1874; Geschwind, 1970). More recent enumerations have begun to recognize the important roles played by both left and right hemispheres, often by delineating their complementary contributions to language comprehension (Beeman, 1998, 2005; Bookheimer, 2002; Caplan, 1992; Ferstl, Neumann, Bogler, & von Cramon, 2008). In general, the left hemisphere appears to be of critical importance to language processing at the local level (e.g., St George et al., 1999). Local-level language comprehension includes processing of letters and single words, the derivation of literal meaning from those stimuli, and relatively passive (non-evaluative) syntactic processing (i.e., McNamara, Kintsch, Songer, & Kintsch, 1996) with a body of neuroimaging studies convincingly demonstrating the importance of left hemisphere function towards these processes (e.g., Bavelier, Corina, Jessard, Padmanabhan, Clark, Karni, et al., 1997; Helenius, Salmelin, Service, & Connolly, 1998; Humphries, Willard, Buchsbaum, & Hickok, 2001).

The right hemisphere, in contrast, is thought to be crucial for processing language at a relatively global level. Global-level language comprehension includes processes such as maintaining coherence at the sentence- and discourse-level across multiple (and perhaps expansive) segments of text, generating inferences, understanding metaphor and jokes, detecting inconsistent elements of a story, and tracking sequences of narrative events. Recent neuroimaging studies have shown greater right relative to left hemisphere activation during these global language processes (Coulson & Wu, 2005; Ferstl, Rinck, & von Cramon, 2005; Knutson, Wood, & Grafman, 2004; Mason & Just, 2004; Sotillo, Carretié, Hinojosa, Tapia, Mercado, López-Martín, & Albert, 2004). Kircher and colleagues (2001) suggest that whereas the left hemisphere is involved in forming semantic associations, the right hemisphere (specifically the right temporal lobe) is involved in the evaluative analysis of sentences, and deriving context-driven meaning (see also, St. George et al., 1999). Finally, patients with brain damage restricted to the right hemisphere show impairments in comprehending natural language and deriving a global discourse message (for a review, see Bookheimer, 2002). For instance, non-aphasic patients with right anterior or posterior brain lesions show difficulty deriving the overall theme of a story, suggesting an inability to comprehend and integrate text into a coherent message (Hough, 1990).

Of course, the above laterality claims are not without criticism. Mason and Just (2004), for example, argue against the view that the right hemisphere is more involved in maintaining discourse coherence and generating inferences, as compared to the left hemisphere. Though they did find greater right than left hemisphere *variation* across relatedness condition (using fMRI), overall activation levels were similar across the two hemispheres. However, Jung-Beeman (2005) posits that both semantic integration and evaluative syntactic processing (e.g., Meyer, Friederici, & von Cramon, 2000) can be right lateralized, with evidence for right hemisphere involvement during language processing emerging from cases involving discourse-level coherence and deriving overall thematic messages from a text (e.g., Beeman, 1993; Beeman et al., 2000; Coulson & Williams, 2005). Some strong evidence for the possibility that the right hemisphere is involved in evaluative syntactic processing comes from a study demonstrating that right-brain-damaged participants show particular difficulty with tasks requiring reassignment of a word's syntactic status within a sentence (e.g., Schneiderman & Saddy, 1988). In an experiment examining this effect within a non-brain-damaged sample, Meyer and colleagues (2000) presented participants with sentences that were either grammatically correct or contained one of several syntactic error types (e.g., case disagreement or word order violations). One participant group was instructed to detect errors, while the other group was instructed to both detect errors and silently repair them. Functional MRI data revealed greater right temporal and frontal lobe activation following instructions to detect and repair as compared to the detection only instructions. These results indicate that the active processing and repairing of syntactic errors is largely contingent upon the right hemisphere, in complement to the relatively automatic and passive syntactic processing commonly observed in the left hemisphere. Thus, while both left and right hemispheres play a role in processing and evaluating syntax, there is emerging (but admittedly not uncontroversial) evidence that actively detecting and operating on syntactic errors is more contingent upon right relative to left hemisphere activity.

Some of these laterality differences are captured by the *Bilateral Activation, Integration and Selection* (BAIS) model (Jung-Beeman, 2005). The BAIS model states that during language processing, the left hemisphere activates small and strongly focused semantic fields related to dominant semantic meaning, with little overlap between activated semantic fields (i.e., Hutsler &

Galuske, 2003). The right hemisphere, in contrast, activates larger and more diffuse semantic fields that activate distant semantic relations (i.e., Taylor, Brugger, Weniger, & Regard, 1999). The clause- and sentence-level semantic integration required for detecting and repairing syntactic errors during discourse processing is argued to be largely reliant upon the right hemisphere (St. George et al., 1999). The differential hemispheric contributions captured by the BAIS model converge nicely with studies demonstrating overall right hemisphere specialization for global processing, and left for local processing of non-language information such as shapes and abstract patterns (e.g., Beeman, 2005; Kimchi & Merhav, 1991; Robertson & Delis, 1986; Robertson & Lamb, 1991; Sergent, 1982; Van Kleek, 1989; Weissman & Banich, 1999).

In sum, both left and right hemispheres are necessary for successful language comprehension, with each hemisphere carrying some degree of specialization for different levels of language processing. The left hemisphere is strongly implicated in the relatively low-level local processing of letter, words, and literal word meaning, whereas the right hemisphere appears to contribute to the active evaluative processing of syntactic information and deriving global meaning. An important question, then, involves understanding how these processes and underlying cortical regions might be influenced by attention-based mediators. We next review evidence that right hemisphere activation is modulated by the experience of state arousal.

Caffeine, Arousal, and the Right Hemisphere

The experience of arousal has been linked to a large network of brain regions including the occipital and fusiform gyri, and frontal and parietal lobes (e.g., Lang, Bradley, Fitzsimmons, Cuthbert, Scott, Moulder, & Nangia, 1998). Arousal states tend to increase activation in these regions primarily in the right hemisphere (i.e., Compton & Weissman, 2002; Heller, 1993;

Heller, Etienne, & Miller, 1995; Levy, Heller, Banich, & Burton, 1983; Liotti & Tucker, 1992; Nitschke, Heller, & Miller, 2000). For instance, when participants view emotionally arousing versus neutral images they show pronounced right lateralization of EEG gamma band activity, thought to index a correlate of widespread cortical networks responsible for processing and understanding arousal states (Keil, Müller, Gruber, Wienbruch, Stolarova, & Elbert, 2001; see also, Müller, Keil, Gruber, & Elbert, 1999). Other researchers have observed similar results using fMRI and event-related potentials (ERPs), with more pronounced right hemisphere activity during periods of emotional arousal (Jünghofer, Bradley, Elbert, & Lang, 2001; Lang, Bradley, Fitzsimmons, Cuthbert, Scott, Moulder, & Nangia, 1998). The above studies have tended to use mood induction paradigms, such as viewing valenced images or listening to high tempo music, to induce emotional arousal (see Bohn-Gettler & Rapp, in press, for a methodological review). Emotional arousal inductions of these types tend to reliably induce processing consequences as well as physiological arousal (Bradley & Lang, 2000; Brunyé, Mahoney, Augustyn, & Taylor, 2009; Lundqvist, Carlsson, Hilmersson, & Juslin, 2009; Nyklicek, Thayer, & Van Doornen, 1997). Of course, arousal can be increased or decreased in a variety of ways beyond such induction paradigms, and individuals commonly modulate their own arousal levels through self-administered caffeine consumption.

Though no studies have specifically examined hemispheric activation asymmetries due to caffeine-induced arousal, two studies suggest that caffeine can increase right hemisphere activity. First, Lorist and Snel (1997) demonstrated that caffeine produces greater right hemisphere EEG activation relative to placebo during the performance of complex attention tasks, a difference that was not replicated in the left hemisphere. Second, related fMRI work suggests that caffeine, relative to placebo, induces greater right but not left hemisphere anterior cingulate activations during a verbal working memory task, suggesting that dopamine-rich regions of the right hemisphere show greater responsiveness to caffeine administration (Koppelstaetter et al., 2008). Some of these effects might be attributed to caffeine's ability to up-regulate levels of brain dopamine, norepinephrine, and serotonin, neurotransmitter systems that appear to be somewhat lateralized to the right hemisphere (Arato, Frecska, MacCrimmon, Guscott, Saxena, Tekes, & Tothfalusi, 1991; Davidson et al., 2004; Fassbender et al., 2006; Oke, Keller, Mefford, & Adams, 1978; Oke, Lewis, & Adams, 1980; Smith et al., 2006).

The present study examined this form of arousal modulation by administering differential doses of caffeine (1,3,7-trimethylxanthine), found naturally in products such as coffee, tea, and chocolate (IOM, 2001). Caffeine is most frequently associated with positive effects on vigilance and mental alertness (for reviews, see Koelega, 1993; Lieberman, 1992, 2001; Smith, 2002; Snel, Lorist, & Tieges, 2004; Spiller, 1997), and recent work has also implicated caffeine as beneficial for some executive control functions such as visual selective attention (Lorist & Snel, 1997; Lorist, Snel, Kok, & Mulder, 1996; Kenemans, Wieleman, Zeegers, & Verbaten, 1999; Ruijter, De Ruiter, & Snel, 2000), task switching (Tieges, Snel, Kok, Plat, & Ridderinkhof, 2007; Tieges, Snel, Kok, Wijnen, Lorist, & Ridderinkhof, 2006), conflict monitoring (Barry, Johnstone, Clarke, Rushby, Brown, & McKenzie, 2007), and response inhibition (Brunyé, Mahoney, Lieberman, & Taylor, 2010; Brunyé, Mahoney, Giles, Lieberman, & Taylor, 2010; Tieges, Ridderinkhof, Snel, & Kok, 2004).

Caffeine, particularly at high doses, up-regulates central nervous system and cardiovascular activity and produces phenomenological experiences of wakefulness, alertness, and arousal (Barry et al., 2005; Leatherwood & Pollet, 1982; Lieberman, 1992; Rusted, 1999; Sicard, Perault, Enslen, Chuffard, Vandel, & Tachon, 1996). These effects have been attributed to caffeine's stimulating effects on dopamine, serotonin, norepinephrine and glutamate activity (largely via adenosine; Ferré, Fredholm, Morelli, Popoli, & Fuxe, 1997; Fredholm, Arslan, Johansson, Kull, & Svenningsson, 1997; Garrett & Griffiths, 1997; Popoli, Reggio, Pezzola, Fuxe, & Ferré, 1998; Smits, Boekema, Abreu, Thien, & van't Laar, 1987; Solinas, Ferré, You, Karcz-Kubicha, Popoli, & Goldberg, 2002), in conjunction with its inhibitory effects on phosphodiesterase (Davis, Zhao, Stock, Mehl, Buggy, & Hand, 2003; IOM, 2001). In the present research, we examine caffeine's indirect effects on brain dopamine through its modulation of adenosine levels. Caffeine has further been implicated in modulating activity in the frontoparietal control network, which extends from the anterior cingulate (AC) through the dorsolateral prefrontal cortex (DLPFC) and to the parietal cortex. This network is thought to be primarily right hemisphere oriented, and to subserve attention, playing an important role in response anticipation and executive control (i.e., Wang, Liu, Guise, Knight, Ghajar, & Fan, 2010). The dopamine-rich brain regions along this network implicate the possibility that dopamine underlies effective attentional control (Davidson et al., 2004; Fan et al., 2003; Smith et al., 2006), and that caffeine may modulate attentional effects.

Some preliminary evidence for this possibility comes from a series of studies demonstrating that caffeine, perhaps through its upregulation of dopamine-rich brain areas such as the ACC, can enhance the executive control of attention (Brunyé et al., 2010a, 2010b; Tieges et al., 2006, 2007). Effectively controlling attention is considered crucial to successfully extracting global meaning from extended discourse (Bialystok, 1993; Bialystok & Mitterer, 1987). For instance, controlling attention modulates the ability to attend to either surface or contextual features of a text, and effectively prioritizing and switching between these levels of analysis (Clark, 1979; Shatz & McCloskey, 1984). If caffeine increases dopaminergic availability in brain networks mediating attentional control, and promotes global processing via right hemisphere arousal mechanisms, then caffeine might be expected to promote global coherence during discourse processing. To examine this possibility, the present research specifically asks whether caffeine can enhance readers' local- versus global-level processing of texts, and specifically, their noticing of errors presented in texts during a proofreading activity.

We also aimed to assess whether any caffeine-based differences in a reader's level of analysis might be attributed to task complexity. Indeed a lower-level analysis of text features may be less complex than a higher-level analysis of global meaning (Jones, Miles, & Page, 1990; Pilott, Chodorow, & Thornton, 2005). As such, any effects of caffeine on local versus global error detection and repair might be attributed to task complexity as opposed to level of analysis. The interactive relationship between caffeine and task complexity is equivocal, with some studies finding no evidence of task complexity effects (e.g., Anderson, Revelle, & Lynch, 1989; Loke, 1992), some studies finding evidence that caffeine selectively enhances performance on low-complexity tasks (e.g., Lorist & Tops, 2003), and still others finding evidence that caffeine selectively enhances performance on high-complexity tasks (e.g., Gruber & Block, 2005). In an effort to avoid possible intervening effects of task complexity, the present study manipulated both level of focus (local, global) and task complexity (low, high).

The Present Studies

Given the apparent functional overlap between global language processes and arousal experiences in the right hemisphere, the extant literature provides evidence to expect that caffeine may increase right hemisphere activity. This might selectively enhance the detection and repair of syntactic errors in extended discourse, but not necessarily improve the detection and repair of local spelling errors. This relationship is also supported by the previously described evidence linking dopamine and the frontoparietal control system with the control of attention during local- versus global-level discourse processing. Caffeine thus offers a potential tool for influencing global processing that has, to date, been applied under relatively restricted circumstances. Recent work in our laboratory provides some preliminary evidence that caffeine induces global processing advantages with both nonverbal and verbal materials. First, we have demonstrated that moderate to high doses of caffeine lead individuals to extract global rather than local elements of visual scenes (Brunyé, Mahoney, Lieberman, & Taylor, 2009; Mahoney, Brunyé, Lieberman, Shirer, Augustyn, & Taylor, 2009). Second, we have found that caffeine can lead to heightened levels of global visual processing (Mahoney, Brunyé, Giles, Lieberman, & Taylor, 2011) again implicating increased global processing under conditions of caffeine-induced arousal. However, neither of these studies has directly examined the potential benefits incurred upon consumption of caffeine towards detecting errors in texts that, sans repair, might lead to later comprehension or memory difficulties. With this application, we specifically tested the hypothesis that caffeine may differentially modulate levels of language processing. We conducted two experiments that involved detecting and correcting errors in extended texts.

Experiment 1

Experiment 1 examined performance on a task involving the detection and repair of both local- and global-level errors in extended real-world discourse. In this experiment, we recruited only low caffeine consumers. To our knowledge, only one study (Anderson & Revelle, 1982) has examined caffeine effects on a ‘proofreading’ task, and this study used only a single dose (approximately 200 mg caffeine), did not detail participant consumption profiles, was primarily concerned with trait impulsivity, and used a between-participants design with a relatively small sample size. In that study, the authors found increased global error detection rates with caffeine, though the results are difficult to interpret more broadly given the above limitations. Building upon that earlier work, we asked whether increasing doses of caffeine (0, 100, 200, 400 mg) would affect error detection and repair rates by interacting with error type (i.e., local or global) and/or error complexity (i.e., simple or complex). Our hypothesis was that that caffeine would improve global error detection and repair rates. We did not have any specific hypotheses related to task complexity (given equivocal data, as described above), and we did not predict any improvement in detecting local errors as this type of process more likely relies on modulation of the left hemisphere, as reviewed above.

Method

Participants

Thirty-six Tufts University undergraduate students (16 male; mean age 19.08; mean BMI 23.2) participated for monetary compensation ($10 USD/hr). All participants were low non-habitual caffeine consumers (maximum of 100 mg/day, M = 42.5 (approx. half cup of coffee), SD = 28.8), did not smoke or use nicotine in any form, were not using prescription medication other than oral contraceptives, and were in good health. 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.

Design

Caffeine was manipulated over four doses (Treatment: 0 mg, 100 mg, 200 mg, 400 mg) in a double-blind repeated-measures design. The range of doses was chosen for its representativeness of caffeine levels found in commonly consumed beverages; for instance, a large (20 oz) coffee at a major franchise coffee house typically contains 350-450 mg caffeine (McCusker, Goldberger & Cone, 2003). We also aimed to keep our dose manipulation comparable to that from other studies to promote comparison across the literature (Fine et al., 1992; Lieberman et al., 2002; Smit & Rogers, 2000), and to examine absolute dose responses (versus doses scaled to body weight) as a tractable solution to military supplementation needs. That is, it is less feasible to create custom-tailored caffeine doses for each individual Soldier based on bodily characteristics (e.g., BMI), versus using absolute doses in future nutritional supplements. For this reason, we opted to assess the effects of caffeine administration in a more general (and dose-response) manner. Each treatment dose was contained within an identical size capsule and administered in a counterbalanced manner across participants. Caffeine was pure anhydrous USP-grade powder, and the placebo was physiologically-inert microcrystalline cellulose powder.

The proofreading task manipulated both the level of the textual errors (local versus global), and the complexity of the errors (simple versus complex), in a 2 x 2 repeated-measures design.

Materials

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 the proofreading task. The BMIS involves rating a series of 16 affective adjectives (e.g., *Peppy, Calm, Active, Tired*) on scales ranging from 1 (*definitely do not feel*) to 4 (*definitely feel*).

Proofreading task. This task, modeled after Anderson and Revelle (1982), involved reading extended passages and detecting intraword and interword errors, a process requiring both proofing and revision, respectively (Troy, 1995). Intraword and interword errors are a commonly accepted categorization scheme for detailing local versus global errors in extended discourse (Weinstein, 1974; Forster, Higgins, & Bianco, 2003). A pool of seven passages was gathered from online news sources and rated by six pilot participants for overall coherence (on a scale from 1 to 5). From this pool, we chose five passages (one practice, four experimental) that did not differ from one another in mean coherence ratings (range 4.13-4.5; $F(4, 20) = 1.06$, $p > .05$, $\eta^2 = .17$), and were similar in readability using Flesch-Kincaid reading ease scores (range 43.5-63.2; Flesch, 1948). Passages described news topics from sports, arts, business, health, and entertainment. Each passage occupied a single printed page (14-pt font; mean word count = 357.6), and was modified to include a total of 32 errors. Eight relatively simple local errors were comprised of misspelled 1-2 syllable words (HAL log-transformed frequency = 10.5; Balota et al., 2007), and eight more complex local errors were comprised of misspelled 3-6 syllable words (HAL log-transformed frequency = 12.9), for a total of 16 intraword errors per passage; misspelled words were constructed so as to represent pronounceable nonwords (e.g., weapons became weapens; development became develepment). Eight relatively simple global errors were comprised of homophone replacements (e.g., weather replaced with whether, and seems with seams), and eight more complex global errors were comprised of morphosyntactic violations, such as subject-verb agreement errors (e.g., Billionaire inventor Tony Stark *enjoy* a lavish lifestyle[…]) and verb tense errors (e.g., …most customers were denied or misled into believing they had *got* approved for low interest […]). Errors were evenly distributed across passage length.

Procedure

Participants visited the laboratory on five separate occasions, first for a normal-consumption practice session, and then four test sessions. Each test session took place in the morning starting between 7 and 9am, was separated by at least 3 days, and preceded by a 12-hour water-only fast. Given that the mean plasma and elimination half-lives of caffeine are approximately 5 hours, the 12-hour fast was deemed a sufficient wash-out period to attenuate any effects of earlier caffeine consumption (Culm-Merdek, von Moltke, Harmatz, & Greenblatt, 2005; IOM, 2001; Statland & Demas, 1980). Though we did not record sleep data, each participant was asked to ensure a normal night's sleep prior to each test session, and in an attempt to control for the effects of circadian rhythm, we scheduled each participant's test sessions at the same morning start time across their sessions.

During the practice session, participants were screened for consumption profiles by completing a 35-item questionnaire probing consumption quantity and frequency for various types of coffee, tea, soft drinks, energy drinks, gum, and medication. Participants also completed the informed consent, which indicated that they would be consuming anywhere from 0 to 400 mg of caffeine across the four test sessions. Finally, they practiced the BMIS and proofreading task. The practice passage was the same for all participants. For all sessions, participants were instructed to read the passage carefully and identify and correct all spelling and grammatical errors they could within a 5-minute timeframe. Test sessions were similar to the practice session, with participants consuming a single capsule (dose) of caffeine along with a cup of water. Approximately 45 minutes after capsule consumption participants began the proofreading task; both passage number and treatment order were counterbalanced across participants. Participants completed the BMIS upon arrival (prior to capsule consumption) and again prior to beginning the proofreading task. Testing was performed in groups of up to 5 participants, with each participant seated in their own workstation.

Results

Self-Reported Mood State

We derived a standard measure of arousal (versus calm) from BMIS data following the reverse-scoring procedures of Mayer and Gaschke (1988). As expected, a repeated-measures ANOVA revealed that mean arousal ratings upon arrival for a test session did not differ as a function of Treatment (caffeine: 0, 100, 200, 400 mg), $F(3,105) = .223$, $p > .05$, $\eta^2 = .01$. Post-treatment, however, there was a significant increase in arousal ratings as a function of Treatment, $F(3, 105) = 3.02$, $p < .05$, $\eta^2 = .08$. Bonferroni-corrected ($\alpha = .017$) paired t-tests comparing the placebo (0 mg) to each of the other Treatment levels (100, 200, 400 mg) revealed higher arousal ratings at the 200 mg, $t(35) = 2.65$, $p < .017$, $d = .44$, and 400 mg dose, $t(35) = 2.82$, $p < .017$, $d = .47$ (placebo versus 100 mg, $p = .03$). Table 1 details adjective ratings as a function of Treatment.

Proofreading Task

Our dependent measure was the detection and correct repair of each error type; in the vast majority of cases, detection was accompanied by a correct repair, with less than one ($M = .84$) incorrect repair per participant. Mean detection and repair rates for the more simple Local errors as a function of Treatment (0, 100, 200, 400 mg) were .89 ($SE = .03$), .91 ($SE = .02$), .90 ($SE = .02$), and .92 ($SE = .02$); for relatively complex Local they were .73 ($SE = .03$), .78 ($SE = .02$),

.76 (*SE* = .03), and .79 (*SE* = .03); for relatively simple Global they were .86 (*SE* = .03), .84 (*SE* = .03), .91 (*SE* = .02), and .87 (*SE* = .02); for relatively complex Global they were .67 (*SE* = .04), .76 (*SE* = .03), .82 (*SE* = .02), and .77 (*SE* = .02).

To examine whether caffeine modulated detection and repair rates, we conducted an omnibus ANOVA with Treatment (4: 0, 100, 200, 400 mg), Error Complexity (2: simple, complex), and Error Type (2: local, global) as independent variables. We found main effects of Error Complexity, $F(1, 35) = 114.53$, $p < .01$, $\eta^2 = .16$, and Error Type, $F(1, 35) = 5.48$, $p < .05$, $\eta^2 < .01$. These effects were qualified by two interactions. An interaction was found between Treatment and Error Type, $F(3, 105) = 2.97$, $p < .05$, $\eta^2 = .01$, suggesting greater Treatment effects in Global conditions. Second, there was some suggestion of greater Treatment effects in Complex conditions, though this interaction did not reach significance, $F(3, 105) = 2.48$, $p = .06$, $\eta^2 < .01$. The three-way interaction term was non-significant ($F < 1$).

To specifically examine Treatment influences on detection and repair rates within each of the error conditions, we conducted four single-factor (Treatment: 0, 100, 200, 400 mg) ANOVAs. As depicted in Figure 1a, within the Complex Global condition we found a significant main effect, $F(3, 105) = 5.69$, $p < .01$, $\eta^2 = .14$. Bonferroni-corrected ($\alpha = .017$) paired t-tests within the Complex Global condition, comparing each of the three Treatment levels (100, 200, 400 mg) to the 0 mg control condition, found significantly higher error detection and repair rates in the 200 mg, $t(35) = 3.42$, $p < .017$, $d = .57$, and 400 mg conditions, $t(37) = 2.65$, $p < .017$, $d = .44$ (placebo versus 100 mg was marginal, $p = .048$). Of the three other conditions, none showed a treatment effect (*p's* > .05, $F_{max} = 1.04$).

Covariate Analysis, Controlling for Arousal

To specifically assess whether arousal mediates caffeine's influence on more Complex Global error detection, we examined whether any observed effects would diminish when controlling for caffeine-induced arousal. Specifically, we calculated post-treatment BMIS arousal difference scores (400mg - 0mg) and entered these data as a covariate in an Analysis of Covariance (ANCOVA) assessing Complex Global error detection rates as a function of Treatment (0, 100, 200, 400 mg caffeine). This analysis revealed a significant interaction between the covariate and Treatment, $F(3, 102) = 41.19$, $p < .01$, $\eta^2 = .53$; specifically, after accounting for caffeine-induced arousal, the effect of Treatment on Complex Global error detection was now nonsignificant, $F(3, 102) = 2.18$, $p = .10$, $\eta^2 = .03$.

Session Order Effects

To assess whether error detection changed as a function of test session, we conducted an omnibus ANOVA with Test Session (4: day 1, day 2, day 3, day 4), Error Complexity (2: simple, complex), and Error Type (2: local, global) as independent variables. Test Session did not produce a main effect, $F(3, 105) = .43$, $p > .05$, $\eta^2 < .01$, or interact with Error Complexity, $F(3, 105) = .12$, $p > .05$, $\eta^2 < .01$, or Error Type, $F(3, 105) = 1.7$, $p > .05$, $\eta^2 < .01$.

Experiment 1 Discussion

This first experiment examined the effects of four doses (0, 100, 200, 400 mg) of caffeine on a task requiring the detection and repair of local- and global-level errors in an extended discourse. Local errors were comprised of relatively simple and relatively complex local surface-level errors (i.e., misspellings), and global errors were comprised of relatively simple and relatively complex global-level errors (i.e., homophone misuse, morphosyntactic violations). Error detection and repair data supported the hypothesis that enhanced global error detection would be observed as a function of increased caffeine consumption. Participants showed higher complex global error detection and repair rates starting at 100 mg (marginally), and asymptoting at 200 and 400 mg, relative to placebo. This result supports the notion that arousal-induced right hemisphere activation may enhance global language processing, allowing for increased detection and repair of syntactic errors requiring the integration of both local- and global-level information towards sentence-level coherence. This effect is likely attributable to caffeine's ability to up-regulate levels of brain norepinephrine and serotonin, neurotransmitter systems that both appear to be generally lateralized to the right hemisphere (Arato et al., 1991; Oke, Keller, Mefford, & Adams, 1978; Oke et al., 1980). These systems have also been implicated in other studies of global language processing, for activities that include identifying and repairing syntactic errors in grammar (Meyer et al., 2000; Schneiderman & Saddy, 1988).

Experiment 2

Caffeine has become the most widely consumed psychoactive stimulant in the world, with average global consumption estimates rising rapidly as caffeine is increasingly incorporated into energy drinks, energy food bars, and chewing gum (IOM, 2001; Reissig, Strain, & Griffiths, 2009; Malinauskas, Aeby, Overton, Carpenter-Aeby, & Barber-Heidal, 2007). Given the prevalence of caffeine in everyday food and drink products, as well as individuals’ increasing reliance on them (Frary, Johnson, & Wang, 2005; Norton, Lazev, & Sullivan, 2011), it is important to understand how caffeine affects performance in individuals with high consumption profiles. To this end, Experiment 2 aimed to replicate the above results in a sample of high caffeine consumers. Habitual caffeine consumers (i.e., > 170 mg caffeine/day) tend to have higher adenosine receptor densities in the brain (Daval, von Lubitz, Deckert, Redmond, & Marangos, 1989; Fastbom, Post, & Fredholm, 1990; Varani, Portaluppi, Merighi, Ongini, Belardinelli, & Borea, 1999), suggesting that they may require relatively large caffeine doses to achieve sufficient adenosine receptor binding to produce significant behavioral responses (Juliano & Griffith, 2004; Kenemans et al., 1999). That is, higher adenosine receptor densities may require larger caffeine doses to produce substantial increases in dopamine, norepinephrine, and serotonin availability. Again, these three neurotransmitter systems are thought to be the primary contributors to caffeine's effects on cognitive functioning, through their effects on the anterior cingulate, parietal lobe, and prefrontal cortex (Coull, Frith, Frackowiak, & Grasby, 1996; Fredholm, Battig, Holmen, Nehlig, & Zvartau, 1999; Garrett & Griffiths, 1997; Lorist & Tops, 2003; Marrocco, Witte, & Davidson, 1994; Nehlig, 1999; Tieges et al., 2004).

With respect to the current project, high consumers represent an interesting case for which processing effects like those observed in Experiment 1 might be obtained only at particularly high consumption levels (i.e., sufficient caffeine may need to be consumed to actually increase arousal and enhance global language processing). Thus, in Experiment 2 we specifically tested whether differences in consumption rates might mediate the potential effects of caffeine on global processing. We only recruited habitual caffeine consumers with average daily caffeine consumption of at least 300 mg. For this group, we hypothesized similar results as in Experiment 1 but only at a high dose. Specifically, we expected our highest dose (400 mg) of caffeine to selectively enhance the detection and repair of Complex Global errors.

Method

Participants

Thirty-eight Tufts University undergraduate students (11 male; mean age 20.03; mean BMI 22.9) participated for monetary compensation ($10 USD/hr). All participants were relatively high caffeine consumers (minimum of 300 mg/day, *M* = 587.6 (approx. 5 cups of coffee), *SD* = 325.9), did not smoke or use nicotine in any form, were not using prescription medication other than oral contraceptives, and were in good health. 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. Two independent-samples t-tests confirmed that participants in Experiments 1 and 2 did not differ as a function of age or BMI (*p*'s > .05).

Design, Materials & Procedure

The design, materials, and procedure were identical to Experiment 1.

Results

Self-Reported Mood State

As in Experiment 1, we derived a standard measure of arousal (versus calm) from BMIS data following the reverse-scoring procedures of Mayer and Gaschke (1988). As expected, a repeated-measures ANOVA revealed that mean arousal ratings upon arrival for a test session did not differ as a function of Treatment (caffeine: 0, 100, 200, 400 mg), $F(3,111) = 1.67$, $p > .05$, $\eta^2 = .04$. Post-treatment, however, there was a significant increase in arousal ratings as a function of Treatment, $F(3, 111) = 8.41$, $p < .01$, $\eta^2 = .19$. Bonferroni-corrected ($\alpha = .017$) paired t-tests comparing the placebo (0 mg) to each of the other Treatment levels (100, 200, 400 mg) revealed higher arousal ratings only at the 400 mg dose, $t(37) = 4.16$, $p < .01$, $d = .67$ (all other *p's* > .09). Table 2 details adjective ratings as a function of Treatment.

Proofreading Task

As in Experiment 1, in the vast majority of cases, detection was accompanied by a correct repair, with less than one (M = .92) incorrect repair per participant. Mean detection and repair rates for more simple Local errors as a function of Treatment (0, 100, 200, 400 mg) were .85 (SE = .03), .85 (SE = .03), .86 (SE = .03), and .89 (SE = .02); for relatively complex Local they were .72 (SE = .02), .68 (SE = .03), .74 (SE = .03), and .72 (SE = .03); for relatively simple Global they were .74 (SE = .04), .77 (SE = .04), .80 (SE = .04), and .80 (SE = .03); for relatively complex Global they were .68 (SE = .04), .65 (SE = .05), .70 (SE = .03), and .78 (SE = .03).

To examine whether caffeine modulated detection and repair rates, we conducted an omnibus ANOVA with Treatment (4: 0, 100, 200, 400 mg), Error Complexity (2: simple, complex), and Error Type (2: local, global) as the independent variables. We found main effects of Error Complexity, $F(1, 37) = 70.86$, $p < .01$, $\eta^2 = .09$, and Error Type, $F(1, 37) = 7.87$, $p < .01$, $\eta^2 = .02$. The Treatment by Error Complexity, $F(3, 111) = .77$, $p > .05$, $\eta^2 < .01$, and Treatment by Error Type, $F(3, 111) = 1.12$, $p > .05$, $\eta^2 < .01$, interactions did not reach significance.

To directly test our a priori hypothesis that caffeine would increase global error detection and repair rates (as in Experiment 1), we conducted four single-factor (Treatment: 0, 100, 200, 400 mg) ANOVAs. As depicted in Figure 1b, within the Complex Global condition we found a significant main effect, $F(3, 111) = 3.74$, $p < .05$, $\eta^2 = .09$. Bonferroni-corrected ($\alpha = .017$) paired t-tests within the Complex Global condition, comparing each of the three Treatment levels (100, 200, 400 mg) to the 0 mg control condition, found significantly higher error detection and repair rates in the 400 mg condition only, $t(27) = 2.72$, $p < .017$, $d = .57$ (all other p's > .53). Of the three other conditions, none showed a treatment effect (p's > .05, $F_{max} = 1.11$).

Testing for Withdrawal Effects

To confirm that our results were not attributable to withdrawal effects in this habitual consumer sample, we conducted four *t*-tests comparing the practice day to the 0 mg day, one for each of the error conditions. Recall that participants were instructed to consume normal daily caffeine amounts on the practice day. No differences were revealed when comparing simple Local rates, $t(37) = .16$, $p > .05$, complex Local rates, $t(37) = .45$, $p > .05$, simple Global rates, $t(37) = .56$, $p > .05$, or complex Global rates, $t(37) = .82$, $p > .05$, across the two sessions. We also confirmed that BMIS arousal scores did not differ between the practice and 0 mg days, $t(37) = .53$, $p > .05$.

Covariate Analysis, Controlling for Arousal

As in Experiment 1, to specifically assess whether arousal mediates caffeine influences on global error detection, we examined whether the effects of caffeine on relatively complex Global error detection would diminish when controlling for caffeine-induced arousal. Specifically, we calculated post-treatment BMIS arousal difference scores (400mg - 0mg) and entered these data as a covariate in an Analysis of Covariance (ANCOVA) assessing complex Global error detection rates as a function of Treatment (0, 100, 200, 400 mg caffeine). This analysis revealed a significant interaction between the covariate and Treatment, $F(3, 108) = 5.69$, $p < .01$, $\eta^2 = .13$; specifically, after accounting for caffeine-induced arousal, the effect of Treatment on Complex Global error detection was now nonsignificant, $F(3, 102) = 2.5$, $p > .05$, $\eta^2 = .06$.

Session Order Effects

As in Experiment 1, to assess whether error detection changed as a function of test session, we conducted an omnibus ANOVA with Test Session (4: day 1, day 2, day 3, day 4), Error Complexity (2: simple, complex), and Error Type (2: local, global) as independent variables. Test Session did not produce a main effect, $F(3, 111) = 1.84$, $p > .05$, $\eta^2 = .01$, or interact with Error Complexity, $F(3, 111) = .55$, $p > .05$, $\eta^2 < .01$, or Error Type, $F(3, 111) = .98$, $p > .05$, $\eta^2 < .01$.

Comparing the Two Experiments

To directly test whether consumption profile modulates the effect of Treatment on Complex Global error detection and repair rates, we conducted a mixed-model 2(Consumption Profile: low, high) x 4 (Treatment: 0, 100, 200, 400 mg) ANOVA on complex Global error detection rates. This analysis revealed an effect of Treatment, $F(3, 216) = 5.88$, $p < .01$, $\eta^2 = .07$, and an interaction between Treatment and Consumption Profile, $F(3, 216) = 3.25$, $p < 05$, $\eta^2 = .04$. This interaction demonstrates that caffeine consumption modulates the extent to which caffeine promotes the detection and repair of complex global errors.

Experiment 2 Discussion

This second experiment examined whether caffeine would affect local- versus global-level error detection and repair in a sample of habitual consumers. The intention was to test whether Experiment 1 effects could be replicated in a sample of participants that better characterizes contemporary consumption profiles. We found evidence of enhanced global-level error detection and repair as a function of increased caffeine consumption. This result supports the notion that arousal-induced right hemisphere activation may increase global language processing, allowing for increased detection and repair of errors requiring the integration of both local- and global-level information towards sentence-level coherence. Unlike Experiment 1, however, the habitual consumers only showed enhanced global processing at the highest dose (400 mg). Thus, the amount of caffeine necessary to induce such arousal clearly differs as a function of consumption rates.

General Discussion

The present experiments were designed to test whether comprehenders' processing of local and global language information could be mediated by attention and arousal. Specifically, we investigated whether caffeine consumption affects the detection and repair of local- versus global-level errors in an extended discourse; Experiment 1 tested this in a low caffeine consumer sample while Experiment 2 tested this with habitual consumers. Results from both experiments provide converging evidence that increasing doses of caffeine enhance individuals' ability to detect and repair global-level syntactic violations such as subject-verb disagreement and verb tense errors. In contrast, caffeine did not increase detection and repair rates for local-level spelling errors. With simple local errors, the results might be attributed to a ceiling effect, with some error detection and repair rates exceeding 90%; with more complex local errors, however, average rates were relatively low (overall M = 74%) across all treatment levels and both experiments, with only minor and nonsignificant increases as a function of treatment in Experiment 1. Thus, caffeine does not appear to affect the detection and repair of local surface-level errors, or promote local performance merely as a function of task difficulty. In contrast, we obtained evidence that caffeine selectively improves the detection and repair of global contextual errors, particularly in the case of complex global errors that require sentence-level integration. With more simple global errors, the fact that caffeine did not influence performance might be related to a ceiling effect specific to this condition; we do note, however, that caffeine produced numeric increases in performance in the simple global condition in both experiments. Future work might consider using even more sensitive tasks, and other error types, to evaluate the effects of caffeine on local versus global language processing.

Early theories of language comprehension strongly implicated the left hemisphere in both semantic and syntactic processing (Milner, Branch, & Rasmussen, 1964; Damasio & Damasio, 1992; Geschwind, 1970). More recent research, however, has demonstrated that maintaining global coherence (St. George et al., 1999) and identifying and repairing grammatical errors (Meyer et al., 2000) during discourse comprehension appear to be especially reliant upon the integrative processes (Federmeier & Kutas, 1999) performed by the right hemisphere. The BAIS model accounts for these differences by positing relatively distributed semantic field activation in the right relative to the left hemisphere, supporting the integration of words and maintaining global coherence (Jung-Beeman, 2005). Caffeine reliably up-regulates levels of brain dopamine, norepinephrine, and serotonin, neurotransmitters systems with various degrees of lateralization (Arato et al., 1991; Oke et al., 1978, 1980). For instance, dopamine D2 binding (which caffeine targets via adenosine; Svenningsson, Nomikos, Ongini & Fredholm, 1997) is greater in the right relative to the left hemisphere (Larisch, Meyer, Klimke, Kehren, Vosberg, & Müller-Gärtner, 1998), and norepinephrine innervation has also been found to be strongly right lateralized (Oke et al., 1978). Further, one recent study has identified hemispheric differences in caffeine-related neurotransmitter activity in language-relevant areas of the human brain (Fink, Wadsak, Savli, Stein, Moser et al., 2009); in this study, positron-emissions tomography (PET) revealed right lateralization of serotonin-1A receptor binding in multiple brain areas including the right superior, middle, and inferior frontal gyri. These brain areas have been implicated in both phonological (story listening) and semantic (word list generation) processing (e.g., Lehéricy, Cohen, Bazin, Samson, Giacomini, et al., 2000). The right hemisphere is also strongly implicated in the experience of affective states, including the high arousal characterizing caffeine's effects on the central nervous system (Schwartz, Davidson, & Maer, 1975; Tucker, Hartry-Speiser, McDougal, Luu, & deGrandpre, 1999; Tucker, Roth, Arneson, & Buckingham, 1977). Given the lateralization of caffeine's effect on neurotransmission in the human brain, the up-regulation of right hemisphere activity may underlie enhanced global error detection and repair.

Our results may also reflect enhanced attentional control through modulation of dopaminergic pathways in a right frontoparietal brain network considered critical for active cognitive control (Davidson et al., 2004; Fan et al., 2003; Smith et al., 2006; Fassbender et al., 2006). This control network is thought to be primarily the locus of the right hemisphere, and plays an important role in the executive control of attention (Wang et al., 2010). Effectively controlling attention is critical to prioritizing and switching between levels of analysis during language processing (Clark, 1979; Shatz & McCloskey, 1984), and the ability to extract global meaning during discourse comprehension (Bialystok, 1993; Bialystok & Mitterer, 1987). It could be the case that caffeine modulates dopamine levels in brain areas critical for effective attentional control during discourse processing, promoting higher level integration and focus on global features of a text. Future research could further examine this hypothesis using advanced neuroimaging techniques, coupled with methodologies that encourage or discourage global or local processing.

The asymptotic effects of caffeine on both error detection and arousal ratings in Experiment 1 exemplify the non-linear effects of caffeine on central nervous system function. Asymptotic effects of caffeine on both lower- and higher-order cognitive performance are quite common (e.g., Lieberman, Wurtman, Emde, Roberts, & Coviella, 1987; Robelin & Rogers,

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1998; Tieges et al., 2006, 2007), and tend to occur at lower doses in participants with low consumption profiles. A high caffeine dose at four times average consumption rates (i.e., 400 mg) did not produce increased subjective arousal or global error detection relative to 200 mg. In contrast, Experiment 2 demonstrated that habitual consumers continue to benefit from doses at the top of our range (i.e., 400 mg; see also, Brunyé et al., 2010a); given average consumption rates exceeding 500 mg, it is likely that even higher doses of caffeine would continue to improve global error detection rates. The difference in asymptotic ranges across our two consumer samples may reflect increased adenosine receptor densities in the habitual consumer brain as documented in previous work (Daval et al., 1989; Fastbom et al., 1990; Varani et al., 1999), suggesting that these samples may require higher caffeine doses to achieve sufficient adenosine receptor binding to produce significant behavioral responses (Juliano & Griffith, 2004; Kenemans et al., 1999). Dose-response manipulations, examining both low and high consumer populations with a variety of processing tasks, make it possible to examine such possibilities; we suggest that future research examining caffeine effects on cognition employ similar designs in their manipulations.

We note that the simple and complex errors used in the present design are unlikely to be ends of a quantitative scale, but likely illustrate more qualitative distinctions. Indeed, the errors might also differ, beyond what we've described, on dimensions including their relational features, their phonological characteristics in comparison to their correct versions, neighborhood density, and other linguistic variables. For the current studies we opted for categorizing the errors in this relatively coarse way to provide a first pass analysis of the nature of the errors that people may differentially detect as a function of caffeine. The present results provide a foundation for future work to more directly characterize the nature of those complex violations, potentially contrasting them on linguistic dimensions that have been articulated in the extant literature (e.g., Balota, Yap, Cortese, Hutchison, Kessler, Loftis et al., 2007). Future research might also more directly assess the effects of caffeine on levels of language processing. The hypotheses outlined in this project would further benefit from methodologies such as functional neuroimaging, in efforts to implicate the neuroanatomical and biochemical mechanisms that may underlie processing enhancements of complex global language processing from caffeine. Such findings would complement the present work and extend potential applications to more basic theory-driven advances in understanding language processing and nutritional neuroscience.

Though caffeine has proven beneficial to task performance across a variety of neurocognitive processes (for reviews, see IOM, 2001; Koelega, 1993; Lieberman, 1992, 2001; Smith, 2002; Snel et al, 2004; Spiller, 1997), some projects have also identified performance decrements. For instance, in certain circumstances caffeine can impair performance on verbal free recall tasks (Arnold et al., 1987; Linde, 1994), and recent work also suggests caffeine can actually reduce the ability to attend to local relative to global features of a visual scene (Mahoney et al., 2011). Global enhancement of language processing may also increase false recall and recognition of words in false memory paradigms, such as the Deese, Roediger, and McDermott (1995) DRM word list task (e.g., Capek & Guenther, 2009). Given that global processing may not always promote task performance, future understandings of any global benefits might investigate whether any enhancements potentially come at a cost to other processing activities.

Given caffeine's popularity, it is important to characterize its effects on brain activity and behavior during real-world tasks. Its use as a stimulant for enhancing arousal and fostering attention is quite commonplace, although its potential application as such a tool during language comprehension, and more generally for other types of comprehension experiences, has gone relatively under-investigated in psychological circles. The present results converge with a small but growing body of evidence demonstrating that caffeine can promote focused attention and memory for both verbal and non-verbal stimuli. Its impact appears to enhance one type of global processing that proves particularly important considering the growing body of work attempting to enhance comprehenders' attention to global concerns in text and conversation (Rapp, van den Broek, McMaster, Kendeou, & Epsin, 2007; Zwaan & Rapp, 2006). Beyond providing evidence for caffeine's potential utility in enhancing such processing, the extant literature affords connections suggesting why such effects should obtain – specifically, through enhancing right hemisphere processing. Thus, the present research reinforces the need for continued study of arousal-driven applications to language processing specifically, and more generally indicates the strength of employing research bridging the gap between applied cognitive psychology and cognitive neuroscience.

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Table 1

Experiment 1 (low consumer) BMIS Adjective Ratings as a Function of Treatment Dosage.

	Treatment							
	0 mg		100 mg		200 mg		400 mg	
Adjective	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Lively	2.44	.81	2.57	.93	2.64	.79	2.61	.90
Happy	2.47	.91	2.81	.92	2.78	.99	2.52	.94
Sad	1.83	.61	1.61	.73	1.75	.69	1.67	.72
Tired	2.69	.86	2.58	.94	2.56	.84	2.11	.89
Caring	2.38	.87	2.61	.93	2.58	.81	2.19	.89
Content	2.61	.84	2.75	.87	2.78	.83	2.53	.97
Gloomy	1.67	.72	1.75	.77	1.78	.87	1.56	.81
Jittery	1.83	.74	1.67	.89	2.25	.97	2.53	1.11
Drowsy	2.64	.89	2.31	.92	2.28	.88	2.03	.81
Grouchy	1.94	1.01	1.81	.89	1.78	.83	1.75	.77
Peppy	1.72	.77	2.08	1.02	2.18	.91	2.33	1.01
Nervous	1.86	.68	1.69	.71	1.92	.87	2.11	1.04
Calm	2.72	.70	2.92	.73	2.86	.76	2.36	.90
Loving	2.33	.89	2.56	.91	2.56	.81	2.39	.93
Fed Up	2.14	.99	1.94	.83	2.06	.92	1.78	.90
Active	2.14	.79	2.47	.97	2.36	.87	2.44	1.05
Overall Arousal	22.94	.37	23.46	.46	24.65	.38	25.14	.34

Note. The BMIS rating scale uses the following anchors: 1 (definitely do not feel), 2 (do not feel), 3 (slightly feel), 4 (definitely feel).

Table 2

Experiment 2 (high consumer) BMIS Adjective Ratings as a Function of Treatment Dosage.

	Treatment							
	0 mg		100 mg		200 mg		400 mg	
Adjective	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Lively	2.39	.79	2.47	.79	2.66	.67	3.00	.62
Happy	2.60	.69	2.53	.79	2.63	.71	2.63	.75
Sad	1.79	.56	1.76	.68	1.89	.56	1.81	.61
Tired	3.23	.75	2.89	.92	2.76	.91	2.84	.95
Caring	2.44	.70	2.53	.65	2.42	.72	2.60	.72
Content	2.67	.71	2.66	.97	2.82	.61	2.84	.77
Gloomy	1.91	.78	1.63	.67	1.87	.84	2.00	.87
Jittery	1.69	.71	1.71	.73	1.66	.71	2.32	.74
Drowsy	2.88	.88	2.63	.99	2.32	.96	2.45	1.05
Grouchy	2.21	.89	1.97	.91	1.95	.89	2.00	.81
Peppy	1.98	.71	1.87	.70	1.95	.66	2.16	.72
Nervous	1.86	.77	1.79	.66	1.92	.75	2.18	.77
Calm	2.67	.75	2.66	.81	2.79	.66	2.66	.78
Loving	2.44	.79	2.34	.75	2.42	.68	2.50	.79
Fed Up	2.19	.76	2.18	.90	2.16	.86	2.53	.83
Active	2.26	.79	2.13	.96	2.18	.65	2.55	.83
Overall Arousal	23.05	.43	22.87	.41	23.55	.38	25.82	.31

Note. The BMIS rating scale uses the following anchors: 1 (definitely do not feel), 2 (do not feel), 3 (slightly feel), 4 (definitely feel).

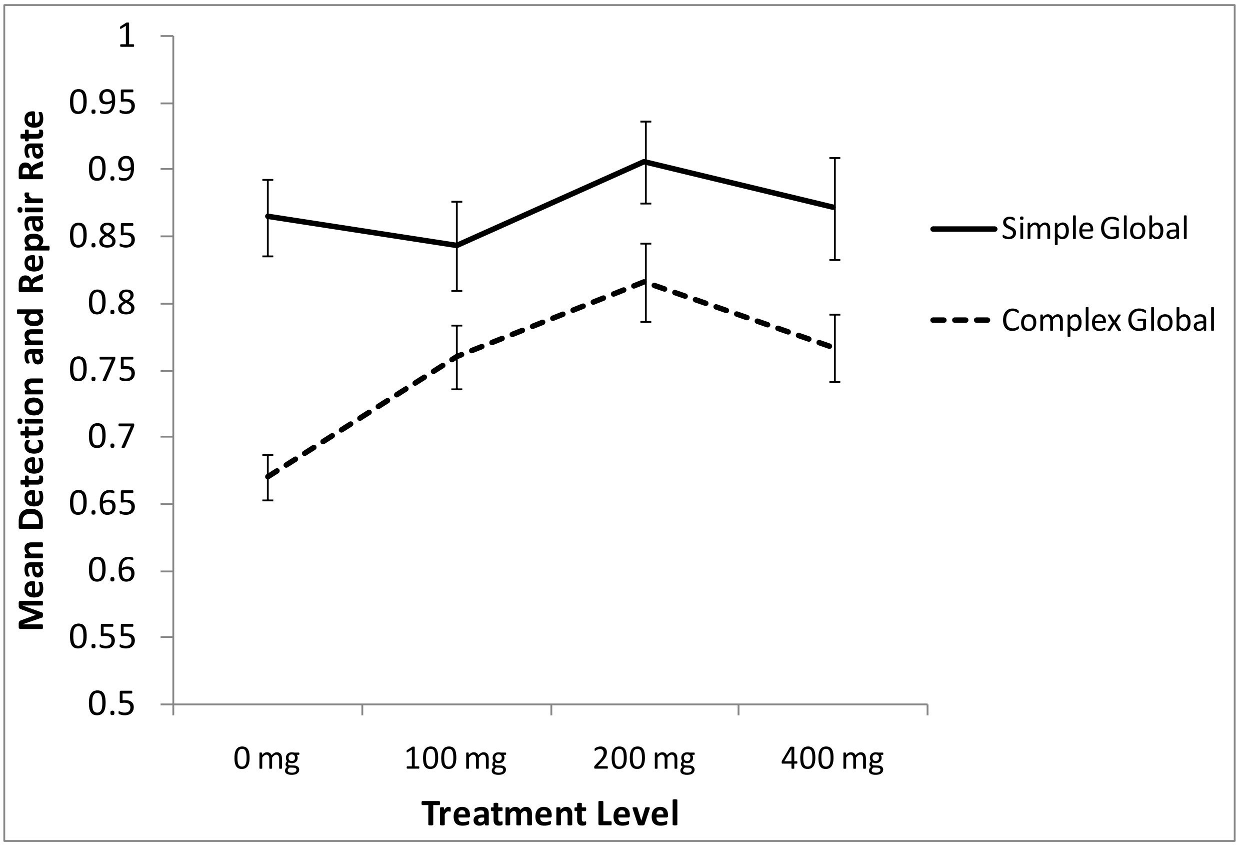

Figure 1a. Experiment 1 mean error detection and repair rates as a function of Treatment dose (0-400 mg) and the two Global error types (simple, complex).

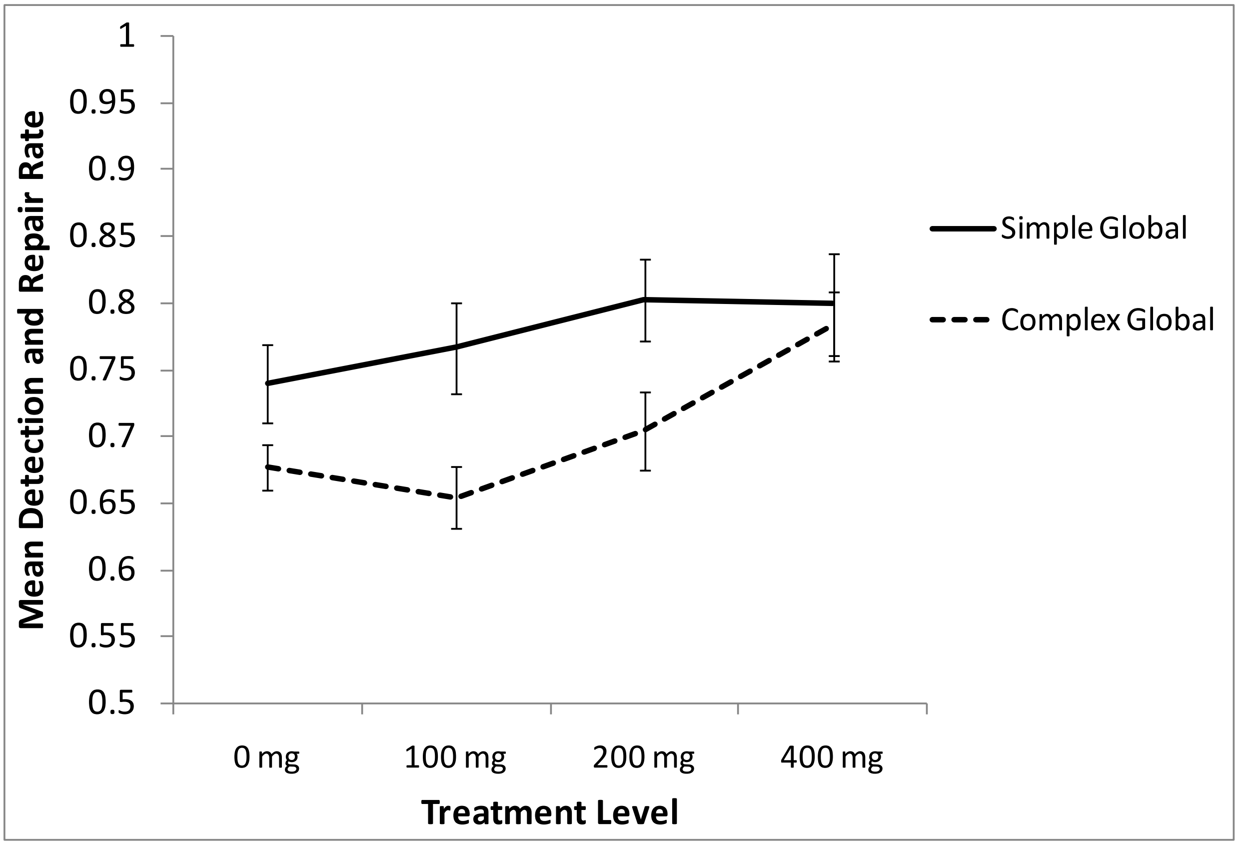

Figure 1b. Experiment 2 mean error detection and repair rates as a function of Treatment dose (0-400 mg) and the two Global error types (simple, complex).