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**Percolating Ideas:
The Effects of Caffeine on Creative Thinking and Problem Solving**

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Abstract

Caffeine is the most widely consumed psychotropic drug in the world, with numerous studies documenting the effects of caffeine on people's alertness, vigilance, mood, concentration, and attentional focus. The effects of caffeine on creative thinking, however, remain unknown. In a randomized placebo-controlled between-subject double-blind design the present study investigated the effect of moderate caffeine consumption on creative problem solving (i.e., convergent thinking) and creative idea generation (i.e., divergent thinking). We found that participants who consumed 200 mg of caffeine (approximately one 12 oz cup of coffee, $n = 44$), compared to those in the placebo condition ($n = 44$), showed significantly enhanced problem-solving abilities. Caffeine had no significant effects on creative generation or on working memory. The effects remained after controlling for participants' caffeine expectancies, whether they believed they consumed caffeine or a placebo, or for changes in mood. Possible mechanisms and future directions are discussed.

Keywords: Caffeine; creativity; convergent thinking; divergent thinking; mood

1. Introduction

Caffeine is the most widely consumed psychotropic drug in the world (Bastia & Schwarzschild, 2003), with 85% of adults in the US consuming at least one caffeinated beverage daily (Mitchell, Knight, Hockenberry, Teplansky, & Hartman, 2014). Consuming caffeine has many cognitive benefits (for review, Glade, 2010): In low to moderate doses, caffeine has been shown to increase people's alertness (Hewlett & Smith, 2007), improve vigilance and motor performance (Fine, K Obrick, Lieberman, Marlowe, Riley, & Tharion, 1994), enhance concentration and attentional focus (Anderson, Revelle, & Lynch, 1989; Rao, Hu, & Nobre, 2005), and elevate mood (Smith, Clark, & Gallagher, 1999; Smith, Sutherland, & Christopher, 2005).

Caffeine's role in creative aspects of cognition, such as idea generation and problem solving, has received surprisingly little attention. In Western cultures, caffeine is stereotypically associated with creative occupations and lifestyles, from writers and their coffee to programmers and their energy drinks, and there's more than a kernel of truth to these stereotypes (Perry, 1999; Weinberg & Bealer, 2004). Given the literature on caffeine and cognition, however, it is not clear whether caffeine should indeed improve creative cognition. The aim of the present study was thus to examine the effect of caffeine on creative cognition, namely creative problem solving (i.e., convergent thinking) and creative idea generation (i.e., divergent thinking).

Some literature presents evidence that lower attentional levels, and namely reduced cognitive control – which is linked with lower prefrontal cortex activity and lower cortical excitability – may be beneficial for creativity (Chrysikou 2019; Thompson-Schill, Ramscar, & Chrysikou, 2009). There is also evidence from frontal lobe patients (Reverberi, Taraldo, D'Agostini, & Skrap, 2005) and brain stimulation studies (Luft, Zioga, Banissy, & Bhattacharya,

2017) suggesting that lower prefrontal activity can indeed be beneficial for some types of creative thinking. Creative idea generation, however, has been shown to involve enhanced cognitive control together with spontaneous thought, as reflected in dynamic coupling between frontoparietal and default mode brain networks (for review, Beaty, Benedek, Silvia, & Schacter, 2016; Zabelina & Andrews-Hanna, 2016). Because caffeine typically enhances concentration and attentional focus (Anderson et al., 1989; Rao et al., 2005), it may differentially affect creative problem solving versus creative generation of ideas.

The Compound Remote Associates (CRA) task—a standard measure of problem solving (i.e., convergent thinking; Bowden & Jung-Beeman, 2003)—presents participants with three seemingly unrelated words and asks them to generate a fourth word that forms a common word or a common compound with the three words. This task thus requires “convergence” on one correct solution. Successful performance on the CRA task relates to better executive control (Lee, Huggins, & Therriault, 2014) and focused attention (Ostafin & Kassman, 2012), so we expected that people who consume a moderate dose of caffeine (vs. placebo) would solve more CRA problems.

Convergent thinking is often contrasted with divergent thinking (creative idea generation), where there is no correct answer but rather a large set of responses that are suitably apt, novel, or interesting. On a typical measure of divergent thinking (e.g., the alternative uses task), participants are asked to generate multiple creative uses for a common object, such as a brick. Responses are scored for the number of uses generated (fluency), as well as for the novelty of each response (originality). Divergent thinking tasks recruit many cognitive processes, including top-down processes related to executive control network and bottom-up, associative processes related to the default-mode network (Benedek & Fink, 2019). These top-down and

bottom-up processes interact in complex ways during idea generation (Beatty et al., 2016; Zabelina & Andrews-Hanna, 2016), so predictions for caffeine and divergent thinking are much less certain than for convergent thinking, although greater executive control should broadly improve creative idea generation. Divergent thinking may be domain-specific (Palmiero, Nakatani, Raver, Belardinelli, & van Leeuwen, 2010), therefore we also examined the effect of caffeine on verbal and visual divergent thinking separately.

In addition to convergent and divergent thinking, we assessed working memory and mood, which both are linked, albeit in complex ways, with creative thinking and problem solving (Baas, De Dreu, & Nijstad, 2008; Smeekens & Kane, 2016; Wiley & Jarosz, 2012). Finally, we sought to examine and control for caffeine expectancy effects. Participants come to caffeine experiments with lay theories about how caffeine enhances mood and cognition—lay theories that are largely supported by research. As a result, expectancy effects are pervasive (e.g., Chan & Maglio, 2019; Dawkins, Shahzad, Ahmed, & Edmonds, 2011) and must be accounted for via research design and assessment. We thus used a double-blind, placebo-controlled design and assessed beliefs about caffeine's effects (Huntley & Juliano, 2012) as possible moderators.

2. Methods

2.1 Participants

Eighty-eight people (60 females, 28 males.), mean age = 21.58 ($SD = 3.33$; 5 unreported), majority White (78%), participated in the current study. Because there is no prior work on the effects of caffeine on creativity, a formal power analysis was not possible, thus we based our projected sample size off of previous work examining the effects of psychotropic drugs on creativity (e.g., Benedek, Panzierer, Jauk, & Neubauer, 2017), and the available time and resources to conduct the project. Our plan was to run the experiment within one semester, or

until the sample size reached 80 people, whichever came last. Participants were recruited via the university newspaper, flyers posted around campus, and on the local National Public Radio station. Participants were invited to participate if they were between 18-35 years of age, consumed between 1-2 cups of caffeinated beverages per day at least 5 days a week, did not smoke, were native English speakers, and took no psychiatric medications or painkillers on a regular basis. The majority of participants reported coffee as their main source of caffeine (81 coffee, 4 tea, 1 energy drinks, 2 soda). Twenty participants drank one cup, and 59 participants drank two cups, of caffeinated beverages per day. Twenty-two participants drank caffeinated beverages five days a week, 23 six days a week, and 42 seven days a week. The study was approved by the local Institutional Review Board, and all participants provided informed consent.

2.2 Experimental Design and Procedure

The study examined the effects of caffeine in a randomized placebo-controlled between-subject double-blind design. Each participant was randomly assigned to the caffeine or control condition. The experimental sessions contained up to six participants at a time and lasted up to 1 hour and 30 minutes. Participants were paid \$15 for their time.

Participants were asked to abstain from any caffeinated or alcoholic beverages from 4 pm on the day prior to the session. They were told that to verify compliance with the abstinence requirements, they would be asked to provide a saliva sample at the beginning of the session (saliva samples were not collected). Sessions took place between 9:00 AM and 3:00 PM.

Participants were told that the university was conducting a study examining the effect of different doses of caffeine on cognitive performance (participants were thus unaware of the placebo condition). Participants took either a 200 mg caffeine capsule or an identical-looking

placebo capsule. Capsules were produced by a local pharmacy specifically for the present study. Participants completed a baseline mood questionnaire (Mood Time 1), took the capsule, and completed various questionnaires for exactly 20 minutes to allow time for caffeine to enter the bloodstream. They then completed the divergent thinking task (ATTA), convergent thinking task (CRA), and a working memory task (Keep Track).

At the end of the experiment participants completed the final mood questionnaire (Mood Time 2), and reported to what extent they expect caffeine to affect them (Caffeine Expectancy Questionnaire). Finally, they were informed that they were randomly assigned to one of the two experimental conditions (caffeine and placebo), and were asked to indicate a confidence level on a sliding scale (1 = *definitely caffeine*, 100 = *definitely placebo*) regarding whether they believed they had taken the caffeine or the placebo capsule. All computer tasks were administered on a Windows PC.

2.3 Measures

2.3.1 Convergent thinking. The *Compound Remote Associates (CRA*; Bowden & Jung-Beeman, 2003) test was used to assess convergent problem solving. Participants were presented with 72 CRAs divided into three blocks (24 problems per block). The order of the problems was pseudo-randomized. For each problem, three cue words were presented in the center of the screen, and participants were instructed to press the spacebar if they knew the solution. Once the spacebar was pressed, the cue words disappeared, and participants typed the solution. The problem remained on the screen for 15 seconds and disappeared after this time in the event that the spacebar was not pressed. If participants typed in the solution, they were asked to indicate if they reached the solution by insight (a subjective Aha! experience; *F* button) or by analysis (a deliberate step-by-step solution; *J* button). They were told: “An insight or Aha! moment often

feels sudden and surprising, as if you just know the solution works with all 3 problem words. In addition, you might be unable to explain how you reached the solution if you solved by insight. Analysis feels more deliberate and you might be more likely to report the steps you took to get to the solution.” Normative data for the CRAs are provided by Bowden and Jung-Beeman (2003). Due to computer error, CRA data failed to record for 17 people, thus CRA data are reported for $n = 71$.

2.3.2 Divergent thinking. The *Abbreviated Torrance Test for Adults (ATTA)*; Goff & Torrance, 2002) was used to assess divergent thinking. The ATTA assesses both verbal (one activity), and figural (two activities) divergent thinking (3 mins each). The verbal activity instructs participants to generate problems that would arise from being able to walk or fly without being in an airplane or a similar vehicle. Figural activities present incomplete figures, and participants are asked to generate drawings incorporating the figures. In all three activities participants are instructed to “be creative” (Nusbaum, Silvia, & Beaty, 2014; Said-Metwaly, Fernández-Castilla, Kyndt, & Van den Noortgate, 2019). Responses are scored for fluency (i.e., the number of generated responses and drawings), and originality (i.e., how novel or original responses are compared to a large pool of normative responses). Scores were summed across the three activities for the final fluency and originality scores. The total divergent thinking score was calculated as the average of z -scored fluency and z -scored originality. Test developers report good reliability for the ATTA ($KR-21 = .84$; Goff & Torrance, 2002).

2.3.3 Working memory. The *Keep Track* task was used to assess working memory (adapted from Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). The task instructed participants to keep track of the last word to appear on the screen from two to five different categories (animals, colors, countries, distances, metals, and relatives). On each trial

participants saw the categories that they were to keep track of on the bottom of the screen, with categories remaining on the screen for the duration of the trial. 15-25 words appeared one at a time and remained on the screen for 2 seconds each. At the end of each trial the categories disappeared, and participants saw a “??,” at which point they wrote down on a sheet of paper the last word they remembered from each of the category for that trial. There were 16 total trials (4 blocks of two, three, four, and five categories) in addition to the 2 practice trials. The dependent measure was recall accuracy. Four participants completed the Keep Track task incorrectly, so Keep Track data are reported for $n = 84$.

2.3.4 Caffeine Expectancy Questionnaire (CaffEQ). The CaffEQ (Huntley & Juliano, 2012) is a 47-item scale that assesses people’s beliefs about how caffeine affects withdrawal/dependence, energy/work enhancement, appetite suppression, social/mood enhancement, physical performance enhancement, anxiety/negative physical effects, and sleep disturbance. Participants were asked to rate each statement on a 6-item Likert-type scale ranging from 1 (*very unlikely*) to 6 (*very likely*), indicating the extent to which they believed each consequence applied to them when they use caffeine. Examples of the items include: “Caffeine picks me up when I am feeling tired,” and “Caffeine improves my attention.” The total CaffEQ score is an average of all the items on the scale. The CaffEQ has excellent psychometric properties, including reliability $\alpha = .96$ (Huntley & Juliano, 2012). Two participants did not complete the CaffEQ, thus data are reported for $n = 86$.

2.3.5 Mood. Mood was evaluated at the beginning (Time 1) and at the end (Time 2) of the session. Participants were asked to indicate on a sliding scale from 0 (*not at all*) to 100 (*very*) to what extent they were feeling *happy*, *sad*, *excited*, *anxious*, *bored*, and *focused*. Two

participants did not complete the Time 1 questionnaire, and one participant did not complete the Time 2 questionnaire, thus $n = 86$ for reported changes in mood.

3. Results

The caffeine and the placebo groups each consisted of 44 participants (16 male and 28 female participants in the caffeine group, and 12 male and 32 female participants in the placebo group). The two groups did not differ significantly in age, $t(82) = 1.40, p = .165$, Cohen's $d = .31$.

3.1 Effects of Caffeine on Convergent Problem Solving

Independent-samples t -test indicated that participants who consumed caffeine solved significantly more CRA problems compared to the control group, $t(70) = 2.37, p = .021$, Cohen's $d = .56$, suggesting a medium-size effect (Table 1; Figure 1). Importantly, analysis of covariance (ANCOVA) indicated that the effect remained significant after controlling for whether participants believed they took the caffeine or the placebo capsule, $F(1,69) = 5.41, p = .023, \eta^2 = .08$. The effect was larger after controlling for individual differences in caffeine expectancy, $F(1,69) = 8.81, p = .004, \eta^2 = .12$. Further, the effect remained significant after controlling for the change in mood from Time 1 to Time 2: Happiness, $F(1,69) = 5.22, p = .026, \eta^2 = .07$; sadness, $F(1,69) = 5.13, p = .027, \eta^2 = .07$; excitement, $F(1,69) = 5.55, p = .021, \eta^2 = .08$; anxiety, $F(1,69) = 5.70, p = .026, \eta^2 = .09$; boredom, $F(1,69) = 5.61, p = .021, \eta^2 = .08$; and focus, $F(1,69) = 5.23, p = .026, \eta^2 = .07$; as well as after including all mood states as control variables, $F(1,61) = 4.57, p = .037, \eta^2 = .07$. Finally, the effect remained significant after controlling for gender, $F(1,69) = 5.67, p = .020, \eta^2 = .08$.

Caffeine and placebo groups did not significantly differ in the CRA problems solved by insight or by analysis, $ps > .140$ (Table 1), indicating that caffeine improves convergent problem solving overall, regardless of the type of the solution.

Further, there were no statistically significant differences in error rates (false alarms) between the caffeine and the placebo conditions for CRA insight, CRA analysis, or CRA total solutions. Finally, participants in the caffeine (vs. placebo) condition were faster at solving CRA problems with insight, $p = .011$, while there were no statistically significant group differences in the speed of responses for CRA problems solved via analysis, nor for the total CRA reaction times (Table 1).

Table 1. The effect of caffeine ($n = 34$) and placebo ($n = 37$) on problem solving (convergent thinking) accuracy, errors (false alarms), and reaction times.

	Caffeine	Placebo				
	Mean (<i>SD</i>)	Mean (<i>SD</i>)	<i>t</i>	<i>p</i>	Cohen's <i>d</i>	95% CI
CRA Total Acc	29.09 (7.30)	25.00 (7.24)	2.37	.021	.56	[.64; 7.53]
CRA Insight Acc	18.68 (8.25)	16.08 (6.35)	1.49	.140	.35	[-.87; 6.07]
CRA Analytic Acc	10.41 (8.64)	8.92 (6.24)	.84	.405	.20	[-2.06; 5.05]
CRA Total Err	8.55 (6.58)	9.30 (9.20)	.39	.698	.09	[-4.61; 3.10]
CRA Insight Err	4.09 (4.17)	5.00 (7.59)	.62	.539	.15	[-3.86; 2.03]
CRA Analytic Err	4.12 (4.46)	4.41 (3.61)	.27	.790	.07	[-2.44; 1.86]
CRA Total RT	6.68 (1.17)	6.87 (1.04)	.73	.470	.17	[-.71; .33]
CRA Insight RT	5.73 (1.29)	6.56 (1.38)	2.60	.011	.62	[-1.46; -.19]
CRA Analytic RT	8.61 (1.89)	7.95 (2.08)	1.38	.174	.33	[-.30; 1.63]

Note. CRA = Compound Remote Associate (CRA) test; Acc = Accuracy (Number of correctly solved problems); Err = Number of Errors; RT = Reaction Time (in seconds). 95% Confidence Intervals (CI) pertain to group differences.

3.2 Effects of Caffeine on Divergent Thinking

Overall, participants generated an average of 13.07 ($SD = 3.57$) responses, with an average originality score of 6.72 ($SD = 3.42$), consistent with the norms reported by the test developers (Goff & Torrance, 2002). Descriptive statistics for the three separate activities of the ATTA are reported in Table 2.

Table 2. Descriptive statistics for the three activities of the Abbreviated Torrance Test for Adults.

	Mean (SD)	Min	Max
ATTA Activity 1 fluency (verbal)	6.52 (2.32)	2	13
ATTA Activity 2 fluency (figural)	1.86 (.41)	1	3
ATTA Activity 3 fluency (figural)	4.67 (2.35)	0	9
ATTA Activity 1 originality (verbal)	2.82 (1.76)	0	7
ATTA Activity 2 originality (figural)	.95 (.69)	0	2
ATTA Activity 3 originality (figural)	2.94 (2.48)	0	9

Note. ATTA = Abbreviated Torrance Test for Adults.

Independent-samples t -test indicated that there were no significant differences in performance on the ATTA divergent thinking test (total divergent thinking, fluency, nor originality) between participants who consumed caffeine capsule and those in the control group, $ps > .406$ (Table 3), suggesting that caffeine did not influence divergent thinking.

Table 3. The effect of caffeine ($n = 44$) and placebo ($n = 44$) on creative idea generation.

	Caffeine	Placebo				
	Mean (<i>SD</i>)	Mean (<i>SD</i>)	<i>t</i>	<i>p</i>	Cohen's <i>d</i>	95% CI
ATTA Total	.06 (.67)	-.06 (.85)	.69	.491	.16	[-.21; .43]
ATTA Fluency	.10 (.97)	-.08 (1.04)	.84	.406	.18	[-.24; .61]
ATTA Originality	.02 (.90)	-.03 (1.11)	.22	.829	.05	[-.38; .47]
ATTA Verbal	.03 (.88)	-.06 (.86)	.52	.607	.03	[-.27; .47]
ATTA Figural	.06 (.59)	-.03 (.64)	.67	.506	.15	[-.17; .35]

Note. ATTA = Abbreviated Torrance Test for Adults. ATTA Total = average of *z*-scored ATTA Fluency and *z*-scored ATTA Originality. 95% Confidence Intervals (CI) pertain to group differences.

We further examined the effect of caffeine on verbal and figural divergent thinking separately, by averaging the *z*-scored fluency and *z*-scored originality on Activity 1 (ATTA Verbal), and by averaging *z*-scored fluency and originality on Activities 2 and 3 (ATTA Figural). Results indicated that participants in the caffeine and the placebo conditions did not significantly differ in terms of their verbal ($p = .607$) or figural ($p = .506$) divergent thinking (Table 3).

3.3 Effect of Caffeine on Working Memory

Independent-samples *t*-test indicated that there were no significant differences in performance on the Keep Track task between participants who consumed caffeine capsule and those in the control group, $p = .679$ (Table 4), indicating that caffeine had no influence on working memory.

Table 4. The effect of caffeine ($n = 43$) and placebo ($n = 41$) on working memory and change in mood (before minus after) caffeine administration (caffeine $n = 44$, placebo $n = 42$).

	Caffeine Mean (<i>SD</i>)	Placebo Mean (<i>SD</i>)	<i>t</i>	<i>p</i>	Cohen's <i>d</i>	95% CI
Keep Track	41.37 (6.60)	40.78 (6.43)	.42	.679	.09	[-.21; .44]
Sadness	-4.59 (15.83)	3.57 (17.79)	2.25	.027	.49	[-15.38; -.95]
Happiness	-3.59 (15.89)	-6.48 (17.32)	.81	.423	.17	[-4.24; 10.01]
Boredom	-.27 (31.06)	6.14 (30.34)	.97	.336	.21	[-19.59; 6.76]
Anxiety	-2.23 (24.99)	.51 (25.14)	.48	.633	.11	[-14.12; 8.65]
Focus	8.23 (24.29)	5.81 (22.34)	.48	.633	.10	[-7.60; 12.44]

Note. ATTA = Abbreviated Torrance Test for Adults. ATTA Total = average of *z*-scored ATTA Fluency and *z*-scored ATTA Originality. 95% Confidence Intervals (CI) pertain to group differences.

3.4 Effects of Caffeine on Mood

Independent samples *t*-test indicated that participants in the caffeine group reported decreased sadness from Time 1 to Time 2 (mean change = -4.59, *SD* = 15.83), while participants in the placebo group reported increased sadness from Time 1 to Time 2 (mean change = 3.57, *SD* = 17.79), $p = .027$. There were no significant differences between the two groups in reported change in mood between Time 1 and Time 2 for happiness, boredom, anxiety, or focus, $ps > .336$ (Table 4).

3.5 Effects of Caffeine Expectancy

Independent samples *t*-test indicated that participants in the caffeine group were approximately at the level of chance for guessing whether they took the caffeine or the placebo capsule ($M = 53.95$, $SD = 31.34$), while participants in the placebo group were more likely to correctly guess that they took the placebo capsule ($M = 72.40$, $SD = 23.38$), $t(85) = 3.08$, $p = .003$, Cohen's $d = .67$, $CI = [-30.35; -6.55]$.

Pearson correlations revealed that believing one consumed the caffeine capsule was significantly correlated with better performance on the working memory task, $r(86) = .28$, $p = .011$, but was not significantly correlated with any of the convergent, $ps > .15$ or divergent thinking variables $ps > .10$, nor with changes in mood, $ps > .09$ (Table 5). Furthermore, individual differences in caffeine expectancy significantly correlated with fewer CRA solutions by insight, $r(69) = -.29$, $p = .015$, but not with any other convergent, $ps > .20$ or divergent thinking variables, $ps > .31$, changes in mood, $ps > .11$ (Table 5), nor with performance on the Keep Track task, $r = -.07$, $p = .52$.

Table 5

Pearson correlation coefficients for participants' beliefs whether they took the caffeine or the placebo capsule, caffeine expectancy (CaffEQ), problem solving (CRA), and creative thinking (ATTA) variables.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Think Caffeine or Placebo	--	.01	-.18	-.11	-.07	-.13	-.13	-.06	-.18	-.01	.17	-.19	.07	-.06	-.05
2. Caffeine Expectancy		--	.16	.29*	-.19	-.07	-.06	-.04	-.11	.007	.09	-.02	.18	.08	.03
2. CRA Total Acc			--	.50**	-.32**	.33**	.32**	.20	.33**	.18	-.07	.06	-.01	-.19	.07
3. CRA Insight Acc				--	-.38**	.07	.08	.03	.02	.10	.00	.13	-.07	-.20	.04
4. CRA Analytic Acc					--	-.07	-.07	-.04	.04	-.17	-.02	.09	-.02	.11	-.08
5. ATTA Total						--	.76**	.76**	.82**	.74**	-.21†	-.05	.05	.19	.10
6. ATTA Fluency							--	.16	.62**	.58**	.00	-.11	.00	.14	.08
7. ATTA Originality								--	.62**	.55**	-.31**	.03	.07	.15	.08
8. ATTA Verbal									--	.22*	-.18	-.07	.11	.11	.03
9. ATTA Figural										--	-.14	-.01	-.05	.19	.15
10. Sadness											--	-.38**	.11	.06	-.26*
11. Happiness												--	-.20†	-.01	.27*
12. Boredom													--	-.10	-.37**
13. Anxiety														--	.16
14. Focus															--

Note. CRA = Compound Remote Associate (CRA) test; ATTA = Abbreviated Torrance Test for Adults; CaffEQ = Caffeine Expectancy Questionnaire. † $p < .10$
 * $p < .05$ ** $p < .01$.

4. Discussion

The present study investigated the effect of caffeine on creative thinking and problem-solving abilities. In a double-blind placebo-controlled design study, we found that in people who consume a moderate dose of caffeine on a daily basis, consuming 200 mg of caffeine (approximately equal to one 12 oz cup of coffee) in a laboratory session significantly enhanced convergent problem-solving ability, but had no effect on divergent thinking or working memory. These effects remained when controlling for individual differences in caffeine expectancy, for believing whether or not one consumed a caffeine capsule, and for changes in mood throughout the session.

The effects of caffeine on creative problem-solving is consistent with the broader literature on caffeine and cognition. Research consistently shows enhanced concentration and attentional focus associated with caffeine consumption (Rao et al., 2005), and such attentional improvements are reasonable mechanisms for changes in convergent problem-solving tasks with correct answers. Further, caffeine's effect on higher-order cognitive processes, such as enhanced response inhibition (Barry, Johnstone, Clarke, Rushby, Brown, & McKenzie, 2007), and enhanced performance on selective visual attention tasks (Brunyé, Mahoney, Lieberman, & Taylor, 2010; Lorist, Snel, Kok, & Mulder, 1996) suggests that enhanced prefrontal activity may facilitate convergent problem solving. Caffeine did not differentially affect insight versus analytical solutions, indicating that caffeine improves convergent problem solving overall, regardless of the approach.

Although not predicted, consumption of 200 mg of caffeine resulted in faster problem-solving by insight, which may reflect faster processing speed associated with caffeine

consumption (Kamimori, McLellan, Tate, Voss, Niro, & Lieberman, 2015). Deliberate, step-by-step analytical solutions were not affected by caffeine.

Notably, caffeine did not affect creative idea generation, measured with the ATTA battery of divergent thinking tasks (Goff & Torrance, 2002). Based on previous literature showing that divergent thinking is linked with increased alpha activity – a common marker of relaxation and network inhibition (for review, Stevens & Zabelina, 2019), and with caffeine resulting in global reduction in EEG power in the alpha activity (Barry, Rushby, Wallace, Clarke, Johnstone, & Zlojutro, 2005), it is reasonable to expect caffeine leading to worse performance on divergent thinking tasks. Other line of work, however, reports complex interactions between top-down and bottom-up cognitive processes during divergent thinking (Beatty et al., 2016; Zabelina & Andrews-Hanna, 2016), therefore it is not clear whether caffeine should indeed have any effect on divergent thinking. It is also possible that 200 mg is not a sufficient dose to impact idea generation during divergent thinking, but higher amounts (e.g., 400 mg) would result in reduced idea generation abilities.

Although the ATTA is widely used and is based on the venerable Torrance Tests of Creative Thinking (Torrance, 2008), its markers of originality are strongly affected by fluency (Silvia et al., 2008), often correlating close to .90 in large samples. Studying ways of separating quantity (fluency) and quality (creativity) has been a major part of the past decade in creativity assessment, such as changing the task instructions to emphasize quality (Said-Metwally et al., 2019), having judges provide subjective ratings of the responses (Benedek, Mühlmann, Jauk, & Neubauer, 2013; Silvia et al., 2008), and using automated methods to evaluate the semantic distance of the responses (Green, 2016; Hass, 2017; Kenett, 2019).

It is possible that the null effects of caffeine on idea generation reflect the emphasis of the ATTA on how many ideas people can generate, not how good the ideas might be. Future work should explore a wider range of tasks and scoring methods that better separate idea quantity and quality. Along those lines, creativity assessment offers many idea-generation tasks beyond the classic divergent thinking framework. Other tasks, like creating original metaphors in figurative language tasks (Beaty, Silvia, & Benedek, 2017; Primi, 2014) or creating witty ideas in humor production tasks (Nusbaum, Silvia, & Beaty, 2017; Ruch & Heinz, 2019), seem promising for future work.

Interestingly, neither caffeine expectancy, i.e., individual differences in caffeine expectancies on one's behavior, nor believing that one took a caffeine or the placebo capsule were associated with problem solving or with idea generation, with the exception of the link between caffeine expectancy and fewer problems solved with insight. Although previous work shows that caffeine expectancy can influence both behavior and physiology (Kirsch & Weixel, 1988), our findings suggest that enhance problem solving was the result of the active ingredient in the caffeine capsules. Future studies will need to further examine the relationship between caffeine expectancy and insight solutions.

Interestingly, participants who consumed the caffeine capsule were approximately at chance for guessing if they were in the caffeine or in the placebo condition. Participants who consumed the placebo capsule, however, were more likely to correctly guess that they were in the placebo condition. These results are in line with previous literature showing that discrimination is typically low after consuming lower doses of caffeine (Griffiths et al., 1990).

A between-subject design was used in the present study because it is difficult to find parallel and interchangeable forms of many creativity tasks. Open-ended creativity tasks can also

have substantial practice effects because participants develop models of the tasks and idea-generation strategies that will carry over from one time to the next (Gilhooly, Fioratou, Anthony, & Wynn, 2007). Nevertheless, a natural next step for future studies is to use a within-subject design to control for individual differences, ideally with counterbalanced tasks. The present experiment used a fixed task order, but varying the task order could reveal if the effects of caffeine shifted over time. The effects of caffeine have a time course that is difficult to estimate for a sample, given variability in body weight and caffeine tolerance, but a fixed order makes it likely that some tasks will be more strongly affected than others.

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