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[Link to publication]

Methylphenidate does not affect convergent and divergent creative processes in healthy adults

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ABSTRACT

An increasing number of healthy people use methylphenidate, a psychostimulant that increases dopamine and noradrenaline transmission in the brain, to help them focus over extended periods of time. While methylphenidate has been shown to facilitate some cognitive functions, like focus and distractor-resistance, the same drug might also contribute to cognitive impairment, for example, in creativity. In this study, we investigated whether acute administration of a low oral dose (20 mg) of methylphenidate affected convergent and divergent creative processes in a sample of young healthy participants. Also, we explored whether such effects depended on individual differences in ADHD symptoms and working memory capacity. Contrary to our expectations, methylphenidate did not affect participants' creative performance on any of the tasks. Also, methylphenidate effects did not depend on individual differences in trait hyperactivity–impulsivity or baseline working memory capacity. Thus, although the effects of methylphenidate on creativity might be underestimated in our study due to several methodological factors, our findings do not suggest that methylphenidate impairs people's ability to be creative.

1. Introduction

In recent years, the number of people using methylphenidate (a psychostimulant that increases levels of dopamine and noradrenaline in the brain) has strongly increased (De Jongh et al., 2008; Maher, 2008; Smith and Farah, 2011). While some of these people use this drug as prescribed medication to treat symptoms of attention-deficit/hyperactivity disorder (ADHD), an increasing number of healthy people use methylphenidate and similar stimulants as cognitive enhancers to boost their ability to concentrate over extended periods of time (Cakic, 2009; Greely et al., 2008; Maher, 2008). While the term *cognitive enhancer* (also referred to as *smart pills* or *botox for the brain*) implies that the effects of such enhancers are unquestionably beneficial, this assumption may be overly optimistic. Indeed, these substances may facilitate cognitive processes that support cognitive stability, such as working memory and response inhibition (e.g., Linssen et al., 2014;

Marquand et al., 2011; Minzenberg and Carter, 2008), but they may simultaneously impair flexible cognitive processes (Fallon et al., 2017), such as those that contribute to creativity (Mohamed, 2016; Müller et al., 2013).

Creativity, the ability to come up with outcomes (e.g., ideas, poems, problem solutions) that are both original and useful, benefits from cognitive flexibility (e.g., Chermahini and Hommel, 2010; Nijstad et al., 2010). Flexible creative processes include seeing associations between concepts that are only remotely related and switching between different task approaches. The most prominent example of a flexible creative process is divergent thinking, the generation of multiple ideas in response to open-ended questions (Guilford, 1967). Alternatively, creative outcomes may result from more persistent processes that require sustained attention, analytical reasoning, and perseverance (Lucas and Nordgren, 2015; Nijstad et al., 2010; Roskes et al., 2012). A prime example of a persistent process is convergent thinking, the recombination of familiar

and closely related information into novel ideas according to certain rules (Boot et al., 2017a; Cropley, 2006). In real life, creativity likely requires a delicate balance between flexible and persistent creative processes rather than one or the other – a balance that has been proposed to be sensitive to modulation by the catecholamines, like dopamine and noradrenaline (Beversdorf, 2019; Boot et al., 2017b; Hommel and Colzato, 2017; Lin and Vartanian, 2018). Recent work has also implicated dopamine and noradrenaline in the modulation of the flexible and persistent processes that contribute to creativity (e.g., Beversdorf, 2019; Chermahini and Hommel, 2010; Mayseless et al., 2013; Tik et al., 2018; Zabelina et al., 2016; Zhang et al., 2014a, 2014b). For example, in a placebo-controlled study, administration of the D2 receptor agonist cabergoline to healthy older people increased the number of generated figural patterns in the option generation task (Ang et al., 2018) and noradrenaline receptor blockade using propranolol benefits performance on the compound remote associates task, a well-known convergent thinking task (Beversdorf, 2019). However, direct evidence for catecholaminergic modulation of the trade-off between flexible and persistent processes in creativity is lacking (Boot et al., 2017b). Here we assess whether increases in catecholamine transmission with methylphenidate (Arnsten and Dudley, 2005; Bymaster et al., 2002; Kuczenski and Segal, 1997) affect creativity depending on the specific creative processes required for the task (Boot et al., 2017b). Specifically, we hypothesized that, by biasing the system towards greater focus but less flexibility, methylphenidate facilitates the persistent creative process (i.e., convergent thinking), while, at the same time, inhibits the flexible creative process (i.e., divergent thinking).

One challenge to isolating cognitive effects of catecholaminergic drugs is that there is substantial inter-individual variability in both the direction and extent of such effects (Cools and Robbins, 2004; Samanez-Larkin et al., 2013). These individual differences in drug effects are thought to reflect dependency on baseline levels of dopamine (Cools and D'Esposito, 2011) and covary with proxy variables. One such proxy variable is trait impulsivity, which is associated with dopamine (auto) receptor availability and striatal dopamine release (Buckholtz et al., 2010; Kim et al., 2013; Lee et al., 2009; Reeves et al., 2012), as well as creativity (Boot et al., 2017d; Feist, 1998). Participants with higher trait impulsivity have been shown to exhibit greater beneficial effects of catecholaminergic drug administration on tasks requiring attention switching and learning (Clatworthy et al., 2009; Cools et al., 2007). Such impulsivity-dependent effects of catecholaminergic drugs correspond well with the enhancing effects of methylphenidate in ADHD (Rapoport et al., 1980; Rosa-Neto et al., 2005), which in turn has been associated with increases in creativity (Boot et al., 2017c). However, negative associations between impulsivity-related variables and cognitive effects of methylphenidate have been found as well. Impulsivity is an important component of novelty seeking (Cloninger et al., 1993; Curtin et al., 1995) and a recent study among healthy participants by Gvirts et al. (2017) showed that the effects of methylphenidate on divergent thinking performance depended on participants' baseline novelty seeking levels. In this study, methylphenidate tended to reduce performance in participants with higher baseline novelty seeking scores (and, presumably, with higher impulsivity scores).

Another proxy variable of baseline dopamine transmission is working memory capacity. Working memory capacity has been associated with dopamine synthesis capacity in the striatum (Cools et al., 2008; Landau et al., 2009), as well as creativity (De Dreu et al., 2012). Prior research found both positive and negative associations between working memory capacity and cognitive effects of methylphenidate (Mehta et al., 2000; Van der Schaaf et al., 2013). Thus, we expected that methylphenidate-effects on creativity can be isolated by considering the proxy variables trait impulsivity and working memory capacity. However, given prior reports of both positive and negative associations between impulsivity-related variables and working memory capacity with cognitive effects of methylphenidate, we examined these associations in an exploratory fashion rather than testing directional hypotheses.

In the present study, we thus set out to investigate methylphenidate effects on convergent and divergent processes in creativity in a sample of healthy participants. We hypothesized that, by increasing focus but reducing flexibility, methylphenidate facilitates convergent thinking, while, at the same time, impairing divergent thinking. In addition, we explored whether these effects depend on individual differences in hyperactivity–impulsivity symptoms of ADHD and working memory capacity, as indices of baseline dopaminergic functioning. Accordingly, our study contributes to our understanding of the neural basis of creative processes in several ways. It is the first to directly assess catecholaminergic modulation of the trade-off between convergent and divergent processes. In addition, it assesses individual variation in methylphenidate's effects on creative processes by examining the role of two heretofore unexplored variables: individual differences in ADHD-symptoms and working memory capacity.

2. Methods and materials

2.1. Participants, design, and procedure

We recruited 48 right-handed Dutch native speakers (28 women) with a mean age of 22.12 years ($SD = 2.39$) to take part in this double-blind placebo-controlled randomized within-subjects study. All but one participant had completed or was currently attending some form of higher education (i.e., university or comparable). The sample size was determined with a power analysis in G*Power (Faul et al., 2007; based on a repeated measures ANOVA with within-subjects factor Drug and between-subjects factor Order of treatment, with $\alpha = 0.05$ and power = 0.80). This analysis indicated that a sample of at least 44 participants would be required to detect pharmacological effects of moderate size ($\eta^2_p = 0.16$; De Dreu et al., 2014) on the variables of interest. Participants were extensively screened prior to participating in the study to exclude any (history of) physical or mental illness, such as ADHD, that could affect their response to methylphenidate. A complete list of the exclusion criteria is shown in Appendix 1. Participants received €100 for their participation.

Participants took part in two sessions during which they received a capsule with 20 mg of methylphenidate or a visually identical placebo. A dose of 20 mg is in accordance with the majority of studies on the effects of methylphenidate on cognition (see Repantis et al., 2010 for a systematic review). The two sessions were scheduled at least one week apart to ensure drug washout. Methylphenidate has a half-life of 2–3 h (Kimko et al., 1999). The two sessions for each subject started at the same time of day and all sessions ended before 5 pm, because dopamine levels naturally rise in the evening (Barbato et al., 2000). The order of the drug and placebo sessions was randomized across participants (24 participants received placebo first). Participants were asked to refrain from drinking alcohol and smoking cigarettes within the 24 h prior to the sessions. Moreover, they were not allowed to drink caffeinated drinks on the testing days. Light snacks were provided during the sessions.

The present experiment was part of a larger study that included language and working memory tasks (including EEG recordings). The data of these tasks are not reported here, because they are not relevant for the present research questions. Session 1 lasted for approximately 5 h. At the start of this session, participants were subjected to a medical screening, consisting of a medical history checklist and blood pressure

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[2] For the second half of participants, we slightly changed this procedure. These participants took part in the medical screening several days prior to the first session. Moreover, these participants completed half of the baseline measures during Session 1 and the other half during Session 2, so that both sessions took approximately 4 h (Methylphenidate effects on) creative performance did not differ between the first and second half of participants (all $Fs < 1.30$, all $ps > .265$).

measurement. Subsequently, participants completed baseline measures of working memory capacity, current ADHD symptoms, (self-reported) creative abilities, and alertness (see below). Approximately 1 h after administration of the capsule containing either 20 mg methylphenidate or a placebo, participants started a series of tasks including an alertness measure, a language task, and several working memory tasks (as part of another study). Methylphenidate levels peak around 2 h after oral administration (Kimko et al., 1999). About 2.5 h after capsule administration, participants completed three creativity tasks that took in total about 20 min to complete (see below). Over the course of the session, participants' blood pressure and heart rate were assessed four times: (1) during the medical screening (approximately 1 h before capsule administration), (2) directly before capsule administration, (3) approximately 1 h after capsule administration, and (4) at the end of the session (approximately 3 h after capsule administration). At Time 1, 3 and 4, participants' subjective mood was also assessed. Session 2 did not include a medical screening and baseline measures, but was otherwise identical to Session 1 and took approximately 4 h.[2]

2.2. Creativity tasks

In both sessions, participants were presented with three creativity tasks, the order of which was counterbalanced across participants. Two participants accidentally received identical creativity tasks in both sessions. These participants were excluded from the analyses.

2.2.1. Alternate Uses Task

We measured divergent thinking using the Alternate Uses Task (AUT; Guilford, 1967). In four separate 2-min trials per session, we asked participants to generate as many new, original ways to use a common object as they could think of. The two sets of four objects (Set 1: brick, cable, towel, book; Set 2: newspaper, can, cardboard box, belt) were matched in terms of the (variance in) flexibility and originality of ideas that were generated in a previous study (data not presented here). Within each session, the objects were presented in terms of Dutch words in randomized order. The order of the sets across sessions was counterbalanced across participants. Subsequently, two trained coders, blind to the conditions that the ideas belonged to, scored participants' ideas in terms of fluency (the number of non-redundant ideas), flexibility (the number of conceptual categories the ideas belonged to), and originality (the extent to which an idea is uncommon and deviates from the ordinary use of an object). To obtain a measure of flexibility, ideas were categorized into different conceptual categories. For example, for the newspaper, the idea "to hit somebody" is coded in the category 'as a weapon', whereas the idea "use to light up the fireplace" is coded in the category 'as fuel'. To obtain a measure of originality, each idea was scored for the extent to which it was novel and uncommon on a 5-point Likert scale (1 = not original at all, to 5 = very original). For example, the idea to use a brick to build a house is very close to the intended use of a brick and is an idea that is mentioned very often; this idea, therefore, received an originality score of "1". Alternatively, the idea to use the brick to make red paint is not very close to the intended use of a brick and is an idea that is mentioned rarely; this idea, therefore, received an originality score of "4". Originality ratings were averaged across all ideas for each individual to correct for differences in fluency. Interrater reliability for both flexibility (Cohen's κs > 0.96, ps < .001) and originality ($ICCs$ > 0.86, ps < .001) was good. Across sessions, participants generated an average of 7.93 ideas (SD = 2.63) in 5.68 categories (SD = 1.53) with an average originality of 1.83 (SD = 0.26), which is comparable to the ideas generated in other studies (e.g., Boot et al., 2017b). In order to control for type I error in the analyses (see Nevicka et al., 2016), for each session, fluency, flexibility, and originality scores were z-transformed and averaged across the four objects into one reliable composite score of divergent thinking ($\alpha_{session\ 1}$ = 0.84, $\alpha_{session\ 2}$ = 0.87). However, separate effects on fluency, flexibility and originality can be found in supplementary analyses in Appendix 2.

2.2.2. Remote Associates Test

We assessed convergent thinking using the Remote Associates Test (RAT: Mednick, 1962). This task required participants to identify associations among words that are not obviously connected. In each session, participants received a set of 10 items in which they were given three words (e.g., jar, stain, blue) and had to generate a word that associated with all of them (i.e., ink). The two sets of items were matched in terms of difficulty based on the solution rate in previous datasets (not presented here) and the order of sets was counterbalanced across participants. This task was self-paced and participants could skip an item if they were unable to retrieve its correct solution. The number of correctly solved items was our measure of convergent thinking. On average, participants solved 5.40 items (SD = 1.53) across sessions.

2.2.3. Alternate Names Task

We measured rule divergent and rule convergent processes in creativity using the recently developed Alternate Names Task (Boot et al., 2017a). During this task, participants were asked to generate as many new names as possible for items in a specific category (e.g., new names for martial arts, new names for pizzas) within 1 min. Participants were thus required to come up with new names that do not factually exist. For each category participants were given three examples of new names. Crucially these sample names all ended with the same letter(s) to cue a certain rule. For example, the sample names 'nikato', 'kai do', and 'sadamo' in the category 'martial arts' all ended with the letter 'o'. Although participants are free to generate any new name they want, their responses are often in line (i.e. converge with) the given cue, but their new names may also diverge from the given cue (Boot et al., 2017a; De Dreu et al., 2014; Marsh et al., 1999). Thus, from the participants' responses, indices for rule convergent thinking (the number of items ending with the cue in the instructions, i.e., 'o') and rule divergent thinking (the number of items not ending with an 'o') could be created. Moreover, we created indices for repetitions (the number of times in which participants consecutively generated names with the same ending), switches (number of times in which participants switched from one ending, e.g., 'e', to another ending, e.g., 'a'), and the number of unique name endings (Boot et al., 2017a; De Dreu et al., 2014). During each session, participants generated new names for two sets of five categories. The sets were matched in terms of rule divergence and convergence based on previous datasets (Boot et al., 2017a). The order of sets across sessions was counterbalanced across participants. We removed names that factually exist (e.g., 'judo' in the category 'martial arts') and duplicates from the data prior to data analysis. Two additional participants were excluded from this particular analysis, because they generated too few valid ideas (M < 1.5) during at least one of the sessions.

Because the resulting variables were strongly skewed, we log-transformed them to approach a normal distribution. Convergent names associated positively with category repetitions (r = 0.98, p < 0.001), and both were z-transformed and aggregated as a measure of rule convergent ideation. Similarly, rule divergent thinking, category switches, and the number of non-redundant endings were z-transformed and formed a reliable index of rule divergent ideation (Cronbach's α = 0.84).

2.3. ADHD symptoms

We assessed hyperactivity–impulsivity and inattention symptoms of ADHD using the 23-item ADHD rating scale for adults (Kooij et al., 2005). For each ADHD symptom, participants rated its frequency in the past 6 months using a 4-point scale, from 1 (never or rarely) to 4 (very often). Sample items of the hyperactivity–impulsivity subscale are "difficulty awaiting turn" and "interrupt or intrude on others". Sample items of the inattention subscale are "easily distracted" and "difficulty organizing tasks and activities". Reliability of the total scale (α = 0.81) and subscales ($\alpha_{hyperactivity-impulsivity}$ = .77; $\alpha_{inattention}$ = 0.72) was good. On average, participants reported a total ADHD score of 1.74 (SD = 0.30,

range = 1.26–2.48), a hyperactivity–impulsivity score of 1.82 ($SD = 0.39$, range = 1.17–2.92), and an inattention score of 1.65 ($SD = 0.32$, range = 1.09–2.27) – scores comparable to those obtained in healthy student samples in previous studies (e.g., Boot et al., 2017d).

2.4. Working memory capacity

Baseline working memory capacity was assessed using a Dutch version of the automated reading span (Daneman and Carpenter, 1980; Unsworth et al., 2005). In this task, participants were required to judge whether presented sentences made sense or not by clicking a button saying 'True' or 'False'. Following each sentence, the participant was asked to memorize a letter that appeared on the screen. After sets of 3–7 sentence–letter combinations, participants were asked to report back the to-be-remembered letters in the current set in the correct order. In total, the task contained 75 sentence judgements and letters to be remembered. The order of the set sizes (each appearing three times) was randomized across participants. Performance on this task was scored as the total number of correctly recalled letters during this task ($M = 60.09$, $SD = 9.70$, range = 32–75).

2.5. Alertness

To assess drug effects on general alertness and vigilance, participants completed two control tasks in both sessions, one prior to capsule administration (the box completion task; Salthouse, 1996) and one approximately 1 h after capsule administration (the number cancellation task; Lewis and Kupke, 1977). The box completion task (Salthouse, 1996) is a paper-and-pencil task in which participants are presented with ten rows of ten square boxes that are still open on one of the sides. Participants were required to close all squares as quickly as possible by drawing a line. Performance on this task was scored in terms of total completion time. The number cancellation task (Lewis and Kupke, 1977) is a paper-and-pencil task that requires participants to scan 28 rows of 35 digits and to cross out all numbers 6 and 9 while ignoring all other digits. Performance on the number cancellation task was scored in terms of total completion time and the number of missed targets.

2.6. Subjective mood and physical symptoms

Subjective mood and current physical symptoms were assessed using visual analogue scales (Bond and Lader, 1974). Participants rated their subjective mood on 16 dimensions (e.g., 'tense – relaxed, 'muzzy – clear-headed') by moving a slider between opposite ends of the dimensions. We calculated factors for *subjective alertness*, *contentedness*, and *calmness* as suggested by Bond and Lader (1974). Similarly, participants rated to what extent they were currently experiencing each of 10 physical complaints (e.g., headache, dry mouth, dizziness). We excluded one participant from the analysis of Drug effects on physical complaints, because of missing values.

2.7. Data analysis

Drug effects on general alertness, mood, and blood pressure were assessed using repeated measures analyses of variance (ANOVAs) with within-subjects factors Drug (methylphenidate vs. placebo) and Time (pre vs. post capsule administration). We tested our hypotheses using repeated measures ANOVAs with the within-subjects factor Drug (methylphenidate vs. placebo) and the between-subjects factor Order of treatment (methylphenidate in session 1/placebo in session 2 vs. the reverse). We applied a Bonferroni correction for multiple comparisons based on the number of creative outcome measures ($\alpha = 0.05/4 = 0.0125$). To further quantify the evidence for the hypotheses involving the main effects of Drug, we calculated Bayes Factors (BF_{10}) using the statistical software JASP (JASP Team, 2018). To assess whether effects depended on participants baseline hyperactivity–impulsivity

symptoms or working memory capacity, we included these (z-transformed) scores and their interactions with Drug and Order as covariates in separate exploratory analyses.[3]

3. Results

3.1. Methylphenidate effects on alertness, mood, and physiology

Participants' performance on the box completion task indicated that there were no differences in general alertness between sessions prior to capsule intake ($t(45) = 0.70$, $p = .485$). Moreover, performance on the number cancellation task indicated that methylphenidate did not affect participants' alertness, either in terms of completion time ($t(45) = -0.16$, $p = .875$) or number of omission errors ($t(45) = -1.58$, $p = .121$). Methylphenidate did not affect participants' subjective alertness ($F(1,45) = 1.68$, $p = .202$, $\eta^2_p = .04$), contentedness ($F(1,45) = 0.15$, $p = .705$, $\eta^2_p < .01$), calmness ($F(1,45) = 1.01$, $p = .321$, $\eta^2_p = .02$), or the degree of physical complaints ($F(1,44) < 0.01$, $p = .979$, $\eta^2_p < .01$) from pre- to post-capsule administration.

As expected, changes in participants' systolic ($F(1,45) = 9.13$, $p = .004$, $\eta^2_p = .17$) and diastolic ($F(1,45) = 7.82$, $p = .008$, $\eta^2_p = .15$) blood pressure from pre to post capsule administration were different for the methylphenidate and placebo sessions. While systolic blood pressure decreased over the course of the placebo session ($M_{t1} = 116.11$, $SD_{t1} = 10.26$; $M_{t2} = 112.86$, $SD_{t2} = 10.37$; $F(1,45) = 18.56$, $p < .001$, $\eta^2_p = .29$), it did not change after methylphenidate administration ($M_{t1} = 115.32$, $SD_{t1} = 10.96$, $M_{t2} = 115.66$, $SD_{t2} = 10.31$; $F(1,45) = 0.12$, $p = .726$, $\eta^2_p < .01$). Diastolic blood pressure increased after methylphenidate administration ($M_{t1} = 70.82$, $SD_{t1} = 7.47$, $M_{t2} = 74.11$, $SD_{t2} = 6.42$; $F(1,45) = 26.31$, $p < .001$, $\eta^2_p = .37$), whereas it did not after placebo ($M_{t1} = 70.72$, $SD_{t1} = 7.24$; $M_{t2} = 71.60$, $SD_{t2 \ time2} = 6.11$; $F(1,45) = 1.89$, $p = .176$, $\eta^2_p = .04$). Also, methylphenidate affected participants' heart rate from pre to post capsule administration ($F(1,45) = 6.74$, $p = .013$, $\eta^2_p = .13$). Heart rate decreased over time in both the methylphenidate and placebo session, but it decreased less strongly after methylphenidate ($M_{t1} = 68.83$, $SD_{t1} = 11.32$, $M_{t2} = 66.04$, $SD_{t2} = 11.32$; $F(1,45) = 7.64$, $p = .008$, $\eta^2_p = .15$) than after placebo administration ($M_{t1} = 67.87$, $SD_{t1} = 13.17$; $M_{t2} = 61.37$, $SD_{t2} = 10.67$; $F(1,45) = 51.43$, $p < .001$, $\eta^2_p = .53$).

3.2. Methylphenidate effects on creative performance

3.2.1. AUT

Fig. 1 shows that for AUT divergent thinking (i.e., a composite score of fluency, flexibility and idea originality), there were no main effects of drug ($F(1,44) = 0.02$, $p = 0.90$, $\eta^2_p < .01$, $BF_{10} = 0.26$) and order of treatment ($F(1,44) = 0.10$, $p = .750$, $\eta^2_p < .01$), nor was there an interaction between drug and order of treatment ($F(1,44) = 0.00$, $p = .993$, $\eta^2_p < .01$).

3.2.2. RAT

None of the main effects on the number of correctly solved RAT items was significant [drug: $F(1,44) = 0.05$, $p = .818$, $\eta^2_p < .01$, $BF_{10} = 0.22$; order: $F(1,44) = 0.06$, $p = .813$, $\eta^2_p < .01$]. Also, we did not find a two-way interaction between drug and order ($F(1,44) = 1.00$, $p = .322$, $\eta^2_p = .02$) on the number of RAT solutions.

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[3] To explicitly test the possibility that hyperactivity–impulsivity and baseline working memory capacity would be related to drug effects in a curvilinear rather than a linear way, we repeated these analysis with participants' squared z-transformed hyperactivity–impulsivity and working memory scores as predictors (Cohen et al., 2013). However, these quadratic variables did not significantly predict (drug effects on) creative performance.
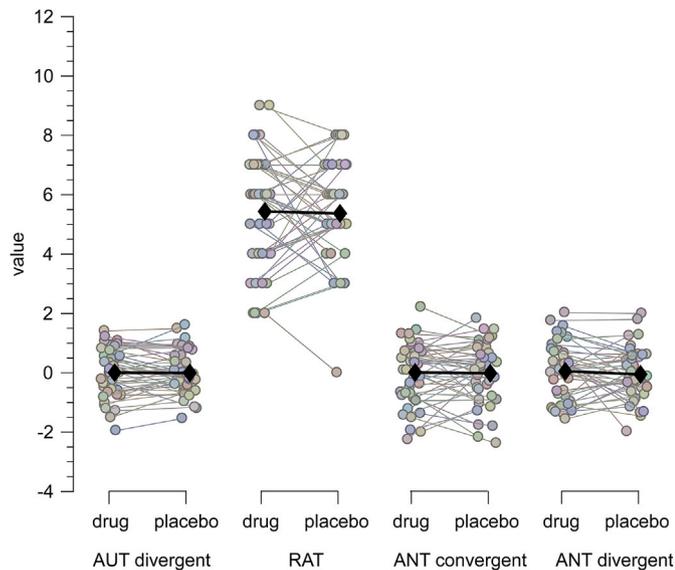
Fig. 1. Performance on the Alternate Uses Test (AUT), Remote Associates Test (RAT), and Alternate Names Task (ANT) in drug (methylphenidate) and placebo sessions.
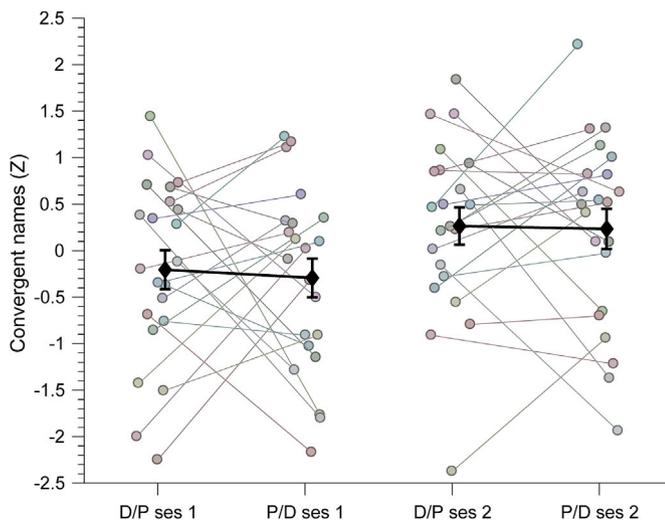
Fig. 2. The number of convergent names that participants generated during the Alternate Names Task in both sessions (displayed ±SE). Regardless of whether participants received methylphenidate (D) or placebo (P), they generated more convergent names during the second session compared with the first session.

3.2.3. Alternate Names Task

For rule convergent thinking during the Alternate Names Task, there were no main effects of drug ($F(1,42) = 0.07$, $p = .796$, $\eta^2_p < .01$, $BF_{10} = 0.22$) and order ($F(1,42) = 0.05$, $p = .830$, $\eta^2_p < .01$). We found a significant interaction between drug and order ($F(1,42) = 20.54$, $p < .001$, $\eta^2_p = .33$), indicating that, regardless of the order of methyl-phenidate/placebo administration, participants generated more conver-gent names in the second session than in the first session (i.e., equivalent to a session effect; see Fig. 2). Follow-up analyses for the Order groups

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[4] Supplementary analyses focusing on participants' Session 1 performance only did not show a main effect of drug on rule convergent ideation ($F(1,42) = 0.09$, $p = .768$, $\eta^2_p < .01$). In addition, for each session and each creativity outcome measure, we also did supplementary univariate ANOVAs with Drug as between-subjects factor. None of the Drug-effects were significant, All $Fs < 1.82$, $ps > .184$.

separately (i.e., methylphenidate in session 1 vs. placebo in session 2 and placebo in session 1 vs. methylphenidate in session 2) confirmed that participants who received methylphenidate during the first session generated fewer convergent names than in the second session in which they received placebo ($F(1,21) = 9.18$, $p = .006$, $\eta^2_p = .30$); likewise, participants who received placebo during the first session generated fewer convergent names than in the second session in which they received methylphenidate ($F(1,21) = 11.41$, $p = .003$, $\eta^2_p = .35$).[4] We do not have a clear interpretation for this session effect and refrain from speculating about it.

For rule divergent thinking during this task, nor the main effects [drug: $F(1,42) = 0.59$, $p = .448$, $\eta^2_p = .01$, $BF_{10} = 0.28$; order: $F(1,42) = 0.12$, $p = .731$, $\eta^2_p < .01$] or interaction-effect [drug × order: $F(1,42) = 0.41$, $p = .526$, $\eta^2_p = .01$] were significant.

3.3. Exploratory analyses of effects involving individual differences

3.3.1. Effects depending on individual differences in hyperactivity–impulsivity symptoms

AUT. For AUT divergent thinking, there were no main effects of drug ($F(1,42) = 0.04$, $p = .838$, $\eta^2_p < .01$), order of treatment ($F(1,42) = 0.19$, $p = .667$, $\eta^2_p < .01$), or hyperactivity–impulsivity scores ($F(1,42) = 0.93$, $p = .340$, $\eta^2_p = .02$). In addition, there were no significant two-way in-teractions between drug and order ($F(1,42) = 0.01$, $p = .911$, $\eta^2_p < .01$), drug and hyperactivity–impulsivity ($F(1,42) = 1.21$, $p = .278$, $\eta^2_p = .03$), or order and hyperactivity–impulsivity ($F(1,42) = 0.23$, $p = .632$, $\eta^2_p = .01$), and no three-way interaction between drug, order, and hyperactivity–impulsivity ($F(1,42) = 0.54$, $p = .469$, $\eta^2_p = .01$).

RAT. None of the main effects on the number of correctly solved RAT items was significant [drug: $F(1,42) = 0.04$, $p = .853$, $\eta^2_p < .01$; order: $F(1,42) = 0.07$, $p = .791$, $\eta^2_p < .01$; hyperactivity–impulsivity: $F(1,42) = 0.11$, $p = .737$, $\eta^2_p < .01$]. Also, we did not find any two-way interactions between drug and order ($F(1,42) = 1.10$, $p = .300$, $\eta^2_p = .03$), drug and hyperactivity–impulsivity ($F(1,42) = 0.36$, $p = .551$, $\eta^2_p = .01$), and order and hyperactivity–impulsivity ($F(1,42) = 0.21$, $p = .650$, $\eta^2_p = .01$). There was no three-way drug × order × hyper-activity–impulsivity interaction ($F(1,42) = 0.08$, $p = .786$, $\eta^2_p < .01$) on the number of RAT solutions.

Alternate Names Task. For rule convergent thinking during the Alternate Names Task, there were no main effects of drug ($F(1,40) < 0.01$, $p = .973$, $\eta^2_p < .01$), order ($F(1,40) = 0.03$, $p = .859$, $\eta^2_p < .01$), or hyperactivity–impulsivity ($F(1,40) = 0.09$, $p = .770$, $\eta^2_p < .01$). We found a significant interaction between drug and order ($F(1,40) = 21.96$, $p < .001$, $\eta^2_p = .35$), indicating that, regardless of the order of methylphenidate/placebo administration, participants gener-ated more convergent names in the second session compared with the first session (i.e., equivalent to the session effect that was described earlier; also see Fig. 2). There were no other significant interactions [drug × hyperactivity–impulsivity: $F(1,40) = 0.18$, $p = .671$, $\eta^2_p = .01$; order × hyperactivity–impulsivity: $F(1,40) = 0.18$, $p = .676$, $\eta^2_p < .01$; drug × order × hyperactivity–impulsivity: $F(1,40) = 4.36$, $p = .043$, $\eta^2_p = .10$].

For rule divergent thinking during this task, none of the main effects [drug: $F(1,40) = 0.85$, $p = .363$, $\eta^2_p = .02$; order: $F(1,40) = 0.02$, $p = .889$, $\eta^2_p < .01$; hyperactivity–impulsivity: $F(1,40) = 3.61$, $p = .065$, $\eta^2_p = .08$] or interactions [drug × order: $F(1,40) = 0.39$, $p = .539$, $\eta^2_p = .01$; drug × hyperactivity–impulsivity: $F(1,40) = 0.01$, $p = .917$, $\eta^2_p < .01$, order × hyperactivity–impulsivity: $F(1,40) < 0.01$, $p = .980$, $\eta^2_p < .01$; drug × order × hyperactivity–impulsivity: $F(1,40) = 2.04$, $p = .161$, $\eta^2_p = .05$] was significant.[5]

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[5] In addition, we explored possible interactions between the drug and inat-tention symptoms of ADHD. None of these interactions were significant (all $Fs < 4.06$, all $ps > .050$).

3.3.2. Effects depending on individual differences in baseline working memory capacity

AUT. We did not find any main effects of drug ($F(1,42) = 0.01$, $p = .943$, $\eta^2_p < .01$), order ($F(1,42) = 0.14$, $p = .707$, $\eta^2_p < .01$), or working memory capacity ($F(1,42) = 0.22$, $p = .644$, $\eta^2_p = .01$) on divergent thinking during the AUT. There were no significant two-way interactions between drug and order ($F(1,42) = 0.07$, $p = .791$, $\eta^2_p < .01$), drug and working memory ($F(1,42) = 3.08$, $p = .087$, $\eta^2_p = .07$), or order and working memory ($F(1,42) = 0.01$, $p = .934$, $\eta^2_p < .01$). The three-way interaction between drug, order, and working memory capacity ($F(1,42) = 1.97$, $p = .167$, $\eta^2_p = .05$) was also not significant.

RAT. For the number of correct solutions during the RAT, we did not find any significant main effects [drug: $F(1,42) = 0.08$, $p = .781$, $\eta^2_p < .01$; order: $F(1,42) = 0.25$, $p = .623$, $\eta^2_p = .01$; working memory capacity: $F(1,42) = 3.03$, $p = .089$, $\eta^2_p = .07$]. There were no significant two-way or three-way interactions [drug × order: $F(1,42) = 0.65$, $p = .425$, $\eta^2_p = .02$; drug × working memory: $F(1,42) = 1.63$, $p = .208$, $\eta^2_p = .04$; order × working memory: $F(1,42) = 0.07$, $p = .791$, $\eta^2_p < .01$; drug × order × working memory: $F(1,42) = 0.12$, $p = .732$, $\eta^2_p < .01$].

Alternate Names Task. For rule convergent thinking during the Alternate Names Task, there were no significant main effects [drug: $F(1,40) = 0.10$, $p = .757$, $\eta^2_p < .01$; order: $F(1,40) = 0.08$, $p = .774$, $\eta^2_p < .01$; working memory capacity: $F(1,40) = 0.32$, $p = .577$, $\eta^2_p = .01$]. We observed the same significant interaction between drug and order ($F(1,40) = 19.26$, $p < .001$, $\eta^2_p = .33$), showing the session effect that was described earlier (also see Fig. 2). None of the other interactions was significant [drug × working memory: $F(1,40) = 0.81$, $p = .374$, $\eta^2_p = .02$; order × working memory: $F(1,40) = 1.89$, $p = .177$, $\eta^2_p = .05$; drug × order × working memory: $F(1,40) = 0.34$, $p = .566$, $\eta^2_p = .01$]. For rule divergent thinking, we did not find any significant main effects [drug: $F(1,40) = 0.58$, $p = .450$, $\eta^2_p = .01$; order: $F(1,40) = 0.11$, $p = .744$, $\eta^2_p < .01$; working memory: $F(1,40) = 0.01$, $p = .916$, $\eta^2_p < .01$] or interactions [drug × order: $F(1,40) = 0.35$, $p = .559$, $\eta^2_p = .01$; drug × working memory: $F(1,40) = 0.10$, $p = .752$, $\eta^2_p < .01$; order × working memory: $F(1,40) = 0.13$, $p = .723$, $\eta^2_p < .01$; drug × order × working memory: $F(1,40) = 0.04$, $p = .846$, $\eta^2_p < .01$].

4. Discussion

In the present study, we aimed to investigate whether methylphenidate affects convergent and divergent creative processes in healthy participants and, if so, whether such effects depend on individual differences in hyperactivity–impulsivity and baseline working memory capacity. We did not find evidence indicating that a single dose of 20 mg methylphenidate affected participants' performance on any of the creative tasks in this study. Also, methylphenidate effects did not depend on individual differences in hyperactivity–impulsivity or baseline working memory capacity. Although participants generated more convergent ideas during one of the creativity tasks in the second session of the study, methylphenidate did not affect this increase in productivity. Methylphenidate significantly increased blood pressure and heart rate compared with placebo, suggesting that our manipulation was successful. However, inconsistent with prior work by Swart et al. (2017), methylphenidate did not affect participants' (subjective or objective) alertness or self-reported mood.

These results are in line with recent findings by Gvirts et al. (2017), who showed that methylphenidate had no main effect on divergent thinking as assessed with the fluency, flexibility, and originality components of the AUT. However, the findings by Gvirts et al. (2017) also showed that methylphenidate effects on divergent thinking depended on individual differences in novelty seeking, which is associated with dopaminergic functioning (Depue and Collins, 1999) and that includes impulsivity as an important component (Cloninger et al., 1993). Our failure to replicate these findings may be due to other components of novelty seeking, such as the willingness to explore things novel and

unfamiliar, that are strongly related to creativity (Gocłowska et al., 2019).

More generally, our study may have had too low power to detect (individual variation in response to) methylphenidate effects on creativity. Generally, effect sizes are small in creativity research, because many factors, including expertise and motivation, determine performance (Amabile, 1996), and subjective scoring of performance is often needed (Farah et al., 2009; Silvia et al., 2008). In line with our findings, several studies focusing on the effects of other drugs that influence dopamine and noradrenaline, such as modafinil, amphetamines and propranolol, did not find straightforward effects on creative processes (Beversdorf, 2019; Farah et al., 2009; Liu et al., 2018; Mohamed, 2016; Müller et al., 2013). The (often marginally) significant effects that were observed in these studies were usually characterized by interactions with individual differences, baseline task performance, or the order in which participants performed tasks. For instance, the administration of modafinil only marginally decreased the number of different conceptual categories used on the Abbreviated Torrance Task for Adults, a divergent thinking task (Müller et al., 2013), and led to enhanced performance on the remote associates task, but only in respondents that had relatively low creative personality traits (Mohamed, 2016). In a similar vein, reducing noradrenaline levels using propranolol promoted performance on convergent thinking tasks, including the remote associates task, but especially when respondents found these tasks difficult or when they were stressed (Alexander et al., 2007; Campbell et al., 2008). Thus, demonstrating drug effects on creative processes may require studies using larger samples, more sensitive tasks, or the consideration of other person characteristics, such as novelty seeking, baselines stress levels, and experienced task difficulty.

In addition, the 20 mg dose of methylphenidate that we administered to participants in our study may have been insufficient to influence creative performance. Previous studies found that methylphenidate increased vigilance and (subjective) alertness (Fröböse et al., 2018; Linssen et al., 2014; Swart et al., 2017; Van der Schaaf et al., 2013), whereas we did not observe such increased subjective or objective alertness. This suggests that our manipulation may not have been sufficiently strong in the current sample. However, other studies have demonstrated methylphenidate effects on cognitive (and creative) performance using a similar dose (Campbell-Meiklejohn et al., 2012; Fallon et al., 2017; Gvirts et al., 2017; Repantis et al., 2010; Swart et al., 2017; Van der Schaaf et al., 2013) and showed that the effects of 20 mg of methylphenidate on response inhibition and memory consolidation were comparable to effects of a higher dose of 40 mg (Linssen et al., 2012). Although participants in the present study completed the creativity tasks towards the end of a 4- to 5-h session and approximately 2.5 h after capsule administration, we think it is unlikely that the interval between drug administration and task performance can explain the present null findings. Plasma levels of methylphenidate peak after approximately 2 h and methylphenidate has a half-life of 2–3 h (Kimko et al., 1999). However, we cannot exclude the possibility that participants' fatigue levels at the end of the session influenced their creative performance in both the drug and placebo session (although this was not reflected in participants' mood and physical complaints as reported immediately after completing the creativity tasks).

Whereas methylphenidate effects on creativity may be underestimated in the present study due to several methodological factors, it is possible also that methylphenidate simply does not affect creative performance. Although the session-related improvement in convergent thinking on one of the tasks could potentially mask a putative subtler effect of methylphenidate, none of the main effects involving methylphenidate were significant and effect sizes were small. In addition, most Bayes factors regarding the main effect of Drug were smaller than 0.33, which has been considered noteworthy evidence for the null hypothesis (Jeffreys, 1998).

These null findings do not provide support for a recently proposed model of dopaminergic modulation of creativity (Boot et al., 2017b).

Based on converging but indirect evidence (e.g., Chermahini and Hommel, 2010; Zabelina et al., 2016; Zhang et al., 2014b), this model proposes that flexible and persistent processes in creativity are modulated by dopamine in frontostriatal brain areas. Moreover, it suggests that the relationship between dopamine in these areas and creativity follows an inverted-U-shaped function, similar to the relationship between dopamine and other cognitive processes (Clatworthy et al., 2009; Van der Schaaf et al., 2013). This model predicts that increasing dopamine levels in the striatum would affect flexible creative processes (such as divergent thinking), whereas increasing prefrontal dopamine levels would influence persistent processes (including convergent thinking), and that the direction of effects depend on people's baseline dopamine levels. Similar trade-off models of flexible and persistent processes have been proposed, but with noradrenergic modulation at their basis (Beversdorf, 2019; Lin and Vartanian, 2018). According to these models, creativity relies on the exploitation of specific mental representations or familiar strategies (closely linked to convergent thinking in the model by Boot et al., 2017b) and the exploration of different mental representations (closely linked with flexibility in the model by Boot et al., 2017b). According to Lin and Vartanian (2018) and Beversdorf (2019), the trade-off between exploitation and exploration in creativity is modulated by noradrenergic activation. Further isolating dopamine from noradrenaline effects on creativity through the administration of more specific drugs may be a next step in uncovering the neurochemical pathways underlying creativity. However, our findings here do not indicate that the presumed modulation of dopamine and noradrenaline levels through the administration of a 20 mg dose of methylphenidate affects either flexible or persistent creative processes.

Although several studies have shown that effects of methylphenidate and more selective dopamine receptor agonists depended on baseline working memory capacity and impulsivity (Cools et al., 2007; Frank and O'Reilly, 2006; Kimberg et al., 1997), these individual differences did not influence methylphenidate effects in the present study. Possibly, the variance in working memory and impulsivity scores in our highly educated, healthy sample was too limited to demonstrate such effects. Also, we assessed individual differences in impulsivity together with hyperactive symptoms of ADHD, using a questionnaire developed for clinical diagnosis of ADHD, whereas previous studies demonstrated impulsivity-dependent effects of methylphenidate and similar substances using the more extensive Barratt Impulsiveness Scale (Patton et al., 1995) that focuses on trait impulsivity (e.g., Cools et al., 2007; Swart et al., 2017). The ADHD questionnaire that we used to assess individual differences in impulsivity may have been less sensitive to such differences in healthy participants. Alternatively, it is possible that methylphenidate effects on creativity depend on other individual differences than those under investigation here, such as baseline creative performance (Farah et al., 2009), novelty seeking (Gvirts et al., 2017), or stress levels (Alexander et al., 2007).

Finally, the present null findings are in line with studies in adults with ADHD that showed that creative performance did not differ between people who used medication to treat their ADHD and people who did not (Boot et al., 2017c; White and Shah, 2011). Also, studies on the effects of methylphenidate on creativity in children with ADHD have obtained mixed results. While some found divergent thinking to be impaired when children were taking methylphenidate (González-Carpio Hernández and Serrano Selva, 2016), others found no effects (Funk et al., 1993) or even enhanced performance after methylphenidate administration (Douglas et al., 1995). Thus, evidence for an effect of medication on creativity in participants with ADHD is inconsistent at present and may be further investigated in future studies.

5. Conclusion

In sum, although methylphenidate effects on creativity may be underestimated in the present study, our findings indicate that the use of methylphenidate as a cognitive enhancer is not unequivocally detrimental to people's ability to generate original ideas and solve creative problems. Although methylphenidate may negatively affect other aspects of performance (in some people) and ethical objections to the use of such substances remain (Greely et al., 2008; Van der Schaaf et al., 2013), our results do not indicate that methylphenidate also affects convergent or divergent creative processes, regardless of individual differences in working memory capacity or impulsivity.

Ethics statement

The experiment was approved by the regional ethical committee for biomedical research (CMO2015/1532), and subjects gave informed consent after they read consent information.

Data availability

The data and analysis scripts used in this article will be made publicly available after manuscript acceptance at the following web address: https://data.donders.ru.nl/collections/published?4. Prior to accessing and downloading the shared data, users must create an account. It is possible to use an institutional account or a social ID from Google, Facebook, Twitter, LinkedIn or Microsoft. After authentication, users must accept the Data Use Agreement (DUA), after which they are automatically authorized to download the shared data. The DUA specifies whether there are any restrictions on how the data may be used. The Radboud University and the Donders Institute for Brain, Cognition and Behaviour will keep these shared data available for at least 10 years.

Declaration of competing interest

No known conflict of interest.

Appendix 1

Exclusion criteria:

- (History of) psychiatric treatment;
- (History of) neurological treatment;
- (History of) endocrine treatment;
- (History of) cardiac or vascular diseases;
- (History of) endocrine/metabolic disease;
- (History of) obstructive respiratory disease;
- (History of) frequent autonomic failure (e.g., vasovagal reflex syncope);
- (History of) clinically significant renal or hepatic disease;
- (History of) epilepsy in adulthood;
- (History of) glaucoma;
- (History of) drug or alcohol dependence;
- One first degree or 2 s degree family members with a history of sudden death or ventricular arrhythmia;
- First degree family member with schizophrenia or bipolar disorder;
- Abnormal hearing or (uncorrected) vision;
- Weekly use of psychotropic medication or recreational drugs over a period of at least 3 months within the last 6 months;
- Use of recreational drugs within 4 weeks prior to participation;
- Use of alcohol within the last 24 h before each test session;
- Uncontrolled hypertension (defined as diastolic blood pressure at rest > 95 mmHg or systolic blood pressure > 180 mmHg);
- Irregular sleep/wake rhythm (e.g., regular nightshifts or cross time-line travel);

- Possible pregnancy or breastfeeding;
- Lactose intolerance.

Appendix 2. Effects of Drug on AUT Fluency, Flexibility and Originality

For AUT fluency (i.e., the number of generated ideas), there were no main effects of drug ($F(1,44) = 1.39$, $p = 0.245$, $\eta^2_p = .03$) and order of treatment ($F(1,44) = 0.11$, $p = 0.746$, $\eta^2_p < .01$), nor was there an interaction between drug and order of treatment ($F(1,44) = 5.06$, $p = 0.030$, $\eta^2_p = .10$) after correcting for multiple comparisons.

For AUT flexibility (i.e., the number of surveyed semantic categories during idea generation), there were no main effects of drug ($F(1,44) = 0.71$, $p = 0.405$, $\eta^2_p = .02$) and order of treatment ($F(1,44) = 0.04$, $p = 0.850$, $\eta^2_p < .01$), nor was there an interaction between drug and order of treatment ($F(1,44) = 2.46$, $p = 0.124$, $\eta^2_p = .05$).

For AUT originality (i.e., the mean rated originality of ideas), there were no main effects of drug ($F(1,44) = 1.96$, $p = 0.169$, $\eta^2_p = .04$) and order of treatment ($F(1,44) = 0.69$, $p = 0.412$, $\eta^2_p = .02$), nor was there an interaction between drug and order of treatment ($F(1,44) = 0.11$, $p = 0.746$, $\eta^2_p < .01$).

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