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Review article

Creativity and ADHD: A review of behavioral studies, the effect of psychostimulants and neural underpinnings

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ABSTRACT

Attention deficit/hyperactivity disorder (ADHD) is a debilitating disorder and most research therefore focuses on its deficits and its treatment. Research on the potential positive sides of ADHD is limited, and although a comprehensive overview of empirical studies on this subject is missing, it has been suggested that ADHD is associated with enhanced creativity. To identify important relations, trends and gaps in the literature, we review 31 behavioral studies on creativity and ADHD, distinguishing different research designs, age groups, creativity measurements and effects of psychostimulants, as well as reflecting the potential underlying neural mechanisms of creativity and ADHD. Most studies find evidence for increased divergent thinking for those with high ADHD scores (subclinical) but not for those with the disorder (clinical). The rates of creative abilities/achievements were high among both clinical and subclinical groups. We found no evidence for increased convergent thinking abilities in ADHD, nor did we find an overall negative effect of psychostimulants on creativity. Neuroscientific findings suggest candidate regions as well as mechanisms that should be studied further to increase our understanding of the relationship between creativity and ADHD. We propose research opportunities to boost the knowledge needed to better understand the potential positive side of ADHD.

1. Introduction

Attention deficit/hyperactivity disorder (ADHD) is a common neurodevelopmental psychiatric disorder, characterized by age-inappropriate levels of inattention and/or impulsivity and hyperactivity (American Psychiatric Association, 2013). The worldwide prevalence has been estimated at 3.4–5.3 % in childhood/adolescence and 2.8 % in adulthood (Fayyad et al., 2017; Polanczyk et al., 2007). For the majority (55–75 %) of people diagnosed with ADHD in childhood, ADHD-symptoms persist into adulthood (Faraone et al., 2006; Polanczyk et al., 2007; Simon et al., 2009). Individuals that meet ADHD criteria experience difficulties across a broad range of situations (e.g., at home, school, and work), which leads to a high personal and societal burden (Le et al., 2014). Also from a social perspective, these people are confronted with challenges, as they are more likely to be bullied, have lower self-esteem, and often end up feeling stigmatized, all of which lower

one's quality of life (Becker et al., 2016; Caci et al., 2015; Lebowitz, 2016; Mueller et al., 2012).

Studies aimed at unraveling the neurobiology of ADHD have shown that ADHD is heritable (Faraone and Larsson, 2019) and have identified the first genome-wide significant risk loci for ADHD (Demontis et al., 2019). Focusing on the brain, structural neuroimaging studies have identified structures in the striatum, but also limbic structures and cortical surface area to be smaller in individuals with ADHD (Frodl and Skokauskas, 2012; Hoogman et al., 2017, 2019; Nakao et al., 2011). The main focus of research in the behavioral and cognitive domains has been on the deficits associated with the disorder, such as deficits in the domains of executive functioning, reward processing, time estimation, and emotional dysregulation (de Zeeuw et al., 2012a; Mostert et al., 2015b; Sonuga-Barke et al., 2010; Willcutt et al., 2005). However, previous work shows that deficits represent only part of ADHD (Coghill et al., 2014a; de Zeeuw et al., 2012a; Mostert et al., 2015b; Nigg et al., 2005).

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It is often mentioned, mainly outside the academic world, that there are positive aspects and strengths associated with ADHD, one of which is creativity, the ability to come up with novel and useful ideas (Runco and Jaeger, 2012). Studies of creativity have shown it to be characterized by increased impulsivity and distractibility, both symptoms of ADHD (Zabelina et al., 2016a; Zaragoza, 2010). Creativity relies on the activation of raw material (e.g., associates, stimuli) from memory that are subsequently applied and transformed into creative ideas (Nijstad & Stroebe, 2006). It follows, first, that creativity is more likely if the activated raw material is unusual. As first described in the associative theory of creativity by Mednick (1962) and later confirmed by Kenett et al. (2014), creative people have a more flexible association network. This association network allows them to easily activate distantly related stimuli that form the basis of unusual associations (Brown, 1973). People with ADHD seem to have a more flexible association network (e.g. White and Shah, 2016). And indeed, ADHD symptoms such as increased impulsivity and distractibility have been linked to increased creative performance (Zabelina et al., 2016a; Zaragoza, 2010). In addition to the unusualness of the raw material, the cognitive processes involved in the transformation and application of this material contribute to creativity. Creative people more easily switch between different associates, perspectives and approaches when solving a problem (Nijstad et al., 2010; Zhang, Sjoerds, & Hommel, 2020). This flexible thinking enables people to generate unusual and creative responses and may also relate to the diffuse attention found in ADHD (e.g. Boot et al., 2017; White and Shah, 2016). At the same time, creativity may also emerge in a more structured, focused and top-down manner (Benedek et al., 2017; Nijstad et al., 2010; Zhang et al., 2020). Strongly relying on executive functions, including shifting and updating, people using this approach focus their attention over an extended period of time to move past standard, less creative responses (Lucas and Nordgren, 2015; Nijstad et al., 2010; Roskes et al., 2012; Nusbaum and Silvia, 2011). Being easily distracted, people with ADHD may fair worse on creativity tasks that capitalize on this more structured and focused approach than on tasks that capitalize on flexible thinking (Boot et al., 2017).

Although the idea that ADHD (symptoms) may be beneficial for creative thought has gained prominence in research in the past decade, this increased attention has resulted in many inconsistent findings (Paek et al., 2016; White and Shah, 2006, 2016). This may in part be explained by the multitude of research designs, samples, and creativity tasks that have been used in this research. The research thus far is not guided by a common framework to organize findings and research efforts, which makes it hard to identify important patterns in the empirical findings.

To our knowledge, there is one meta-analysis on psychopathology (including ADHD) and creativity that shows a negative association between ADHD and creativity (Paek et al., 2016). However, this meta-analysis was not aimed specifically at the link between ADHD and creativity, and therefore choices in the design of the study were sub-optimal for our understanding of this link.

With the aim to increase our understanding of the link between ADHD and creativity, the current systematic review aims at an overview of all the behavioral studies involving the link between ADHD and creativity that have been published so far with a focus on a number of specific aspects (e.g. clinical versus non-clinical ADHD) that were not part of the previous meta-analysis (Paek et al., 2016). For this purpose, we first give an overview of the most common creativity measurements to provide a useful framework, after which we describe and summarize behavioral studies that have investigated the link between ADHD (symptoms) and creativity, separately for research design (clinical case-control design and population based trait studies), age group (children/adolescents and adults), type of creativity assessment (divergent, convergent thinking and creativity abilities/achievements) and the effect of ADHD medication on creative performance. We believe that we can bring the field further not only by optimizing the review of behavioral studies; we also believe that by taking a closer look at the neurobiology (genetic factors and brain characteristics) of creativity and

ADHD we can generate new insights into the link between the two. For example, insofar as creativity and ADHD and its associated symptoms are increasingly understood in terms of neuroendocrine and neuro-cognitive systems (Beaty et al., 2019, 2014; Beversdorf, 2019), understanding the relation between ADHD and creativity may be quite revealing about the neural bases of creativity.

With this broad, interdisciplinary focus, we seek to advance research and our understanding of the intriguing link between ADHD and creativity. Currently, ADHD is mainly associated with negative associations such as underperforming and undesired behavior (Daley and Birchwood, 2010; Loe and Feldman, 2007), which leads to negative associations (Brandau et al., 2007) that end up stigmatizing people with ADHD (Lebowitz, 2016). A better understanding of the relation between ADHD and creativity can counteract this stigmatization by focusing more on the positive characteristics of people with ADHD.

2. How is creativity defined and how can it be measured?

There are many discussions and reviews about the definition, level, and research approach to creativity (see e.g., Kozbelt et al., 2010; Montag et al., 2012; Runco and Jaeger, 2012; Simonton, 2003). **Most often**, creativity is defined as the generation of ideas or products that are original as well as useful (Amabile et al., 1996; Montag et al., 2012; Runco and Jaeger, 2012; Simonton, 2003). Many different processes are involved in creativity, which, according to the dual pathway to creativity model, can be divided into two broad types: *cognitive flexibility* and *cognitive persistence* (Boot et al., 2017d; Mekern et al., 2019; Nijstad et al., 2010). Cognitive flexibility, the ease with which people can switch to a different approach or consider a different perspective, involves processes such as seeing associations between concepts that are only remotely related and switching between different task approaches (Nijstad et al., 2010). The most prominent example of cognitive flexibility is divergent thinking, which is the ability to generate many alternative options to a single open-ended problem (Guilford, 1967). Many different tasks exist to measure divergent thinking (see Table 1), two of the most well-known being the Torrance Test of Creative Thinking (TTCT; Torrance, 1968) and the Alternate Uses Task (Guilford, 1967). The TTCT consists of figural subtests, such as the incomplete figure task where one has to add lines to existing figures to make new ones, and verbal subtests such as the consequences task where one has to list consequences of improbable situations. In the Alternate Uses Task, respondents have to think of as many alternative uses for common objects (e.g., a brick). Performance on these tasks are generally rated by trained judges on the following outcome measures: 1. *Fluency* is a measure of idea generation capacity and is scored by the total number of ideas generated, 2. *Flexibility* represents the ability to switch between different categories and is scored by the number of nonredundant conceptual categories from which the generated ideas were sampled, and 3. *Originality* represents the relative infrequency of those same answers throughout the sample.

The second broad type of creative thinking is cognitive persistence, defined as the degree of sustained and focused task-directed cognitive effort. It is characterized by sustained, goal-directed processes needing focused attention over an extended period of time (Lucas and Nordgren, 2015; Nijstad et al., 2010; Roskes et al., 2012). Initially, this leads to obvious and non-original ideas but persistence on the subject, and analyzing and exploring possibilities along a certain line will eventually lead to more original ideas. A prime example of a persistent process is convergent thinking, although the definition and operationalization of convergent thinking varies considerably across studies. Sometimes convergent thinking is defined as a series of cognitive operations that converge on the correct answer to a problem (Cropley, 2006). Yet other researchers conceptualize convergent thinking as thinking along a certain line (Boot et al., 2017a, 2017b, 2017c, 2017d) or the recombination of closely related knowledge into multiple ideas, with convergent thinking being expressed in a limited range of semantic categories that

Table 1
Overview of creativity measures.

Measure	Description	Reference
<i>Divergent thinking</i>		
Alternative (unusual) Uses task (UUT/AUT)	Participants generate as many alternative uses for common objects (e.g., brick, tin can) as possible. Ideas are coded by trained judges for fluency, flexibility, originality and, sometimes, elaboration.	Guilford, 1967
Torrance Tests of Creative Thinking (TTCT)-figural	Six subtests, e.g., participants draw as many possible figures using provided shapes (e.g., triangles). Drawings are rated for fluency, flexibility, originality and elaboration by trained coders.	Torrance, 2006
Torrance Tests of Creative Thinking (TTCT)-verbal	Six subtests, e.g., participants come up with as many possible causes that lead to an action shown in a drawing as possible. Ideas are rated for fluency, flexibility, originality and elaboration by trained coders.	Torrance, 2006
Abbreviated Torrance Test for Adults (ATTA)	Participants make unusual pictures on the basis of a provided incomplete figure. Pictures are rated for fluency, flexibility, originality and elaboration by trained coders.	Goff and Torrance, 2002
Wallach-Kogan Creativity Test	Several verbal and figural subtests, such as the Instances subtest where participants generate as many possible instances of a class concept (e.g., things that are round, things that move on wheels). Task performance is scored for fluency and uniqueness by trained coders.	Wallach and Kogan, 1965
Ward animal task	Participants imagine and draw two different animals that live on another planet. Drawings are coded by trained judges for divergence from 5 common features of animals on earth (e.g., bilateral symmetry).	Ward, 1994
Recently activated knowledge task	Participants imagine and draw a new and different toy after being shown three examples that have 3 features in common (e.g., presence of a ball). Drawn toys are coded for whether they included these 3 features.	Smith et al., 1993
Cell Phone task	Participants list as many new and interesting features for an innovative cell phone for college students as possible. Ideas are coded by trained judges for fluency, flexibility, originality and elaboration.	Cheng et al., 2008
Word association task	For 25 trials, participants say the first word that comes to mind when hearing a common word. Responses are scored for semantic distance with the provided word using semantic analysis.	Merten and Fischer, 1999
Problem construction task	Participants read about four problematic situations. They are asked to redefine the problem in terms of four aspects (e.g., alternative goals, constraints) by choosing one of four given problem definitions that vary in usefulness (high vs. low) and originality (high vs. low).	Mumford et al., 1996
Creativity Test for Preschoolers and Pupils	Six subtests, e.g., participants come up with different ways to move about. Ideas are rated for fluency and flexibility by trained coders.	Krampen, 1996
Pasta task	Participants are given five primes of non-existing pasta names all ending with an "i" (e.g., maloveni, paragoni), and then generate as many new pasta names as possible	Boot et al., 2017b

Table 1 (continued)

Measure	Description	Reference
	within 2 min. Indices for divergent thinking are the number of items not ending with an 'i', category switches which are number of times in which participants switch from one ending, e.g. 'i', to another ending, e.g. 'a', and the number non-redundant endings.	
Spatial creativity task	Subjects are presented with an array of various geometric shapes and are asked to create as many different recognizable objects as possible from these shapes. They were given 2 min to do so.	Barkley et al., 1996a
<i>Convergent thinking</i>		
Remote Associations Task (RAT)	Participants generate a word that connects three stimulus words (e.g., black, bean, break; answer: coffee). Correct solution: yes/no.	Mednick, 1962
Group Embedded Figures Task	Participants regroup the elements of a geometric design in ways that reveal the figures embedded in it, 9 trials per session.	Noppe, 1996
Maier's Two-String Problem	Participants have to tie two strings together that hang from the ceiling on either side of a room and that are too short to hold one and then grab the other. Tools are present (e.g., spanner). Respondents are asked to come up with as many solutions as possible.	Maier, 1931
Pasta task	Participants are given five primes of non-existing pasta names all ending with an "i" (e.g., maloveni, paragoni), and then generate as many new pasta names as possible within 2 min. Indices for convergent thinking are the number of items ending with an 'i', the cue given in the instructions and category repetitions which are the number of times in which participants consecutively generate pasta names with the same ending. This task assesses the ability to think along a certain line, as expressed in rule-convergent thinking (with generated names following an implicit cue that is given in the task instructions) and in category repetitions, which are the number of times in which participants consecutively generate pasta names with the same ending (i. e. using the same rule).	Boot et al., 2017b
Creative imagery task	In each of six trials, participants create an object that falls into a given category (e.g., furniture) using three 3-dimensional figures (e.g., sphere). This task measures the ability to recombine closely related knowledge into ideas. Objects are coded by trained raters for originality and practicality.	Finke, 1990
<i>Creative abilities and achievements</i>		
Creative Achievement Questionnaire (CAQ)	Participants mark recognized, concrete, and rank-ordered creative achievements in ten domains (e.g., visual arts, sciences, music). Scores for each domain are summed together to yield a creative achievement score.	Carson et al., 2005
Creativity Behavior Scale	Respondents rate how often they engage in nine creative behaviors in the workplace (e.g., I often think of original solutions to problems)	Janssen, 2001
Creative ability scale		

(continued on next page)

Table 1 (continued)

Measure	Description	Reference
Creative imagery task	Students rate themselves relative to their same-aged peers on a range of creative traits (e.g., reflecting artistic or writing ability).	DuPaul et al., 2017
	In each of six trials, participants create an object that falls into a given category (e.g., furniture) using three 3-dimensional figures (e.g., sphere). Objects are coded by trained raters for originality and practicality.	Finke, 1990

are considered during idea generation (Nijstad and Stroebe, 2006). This is why convergent thinking can best be understood as a collection of related cognitive processes in the context of problem solving, including honing in on the best solution to a problem, reapplying set techniques, sticking to set rules, and sticking to a narrow range of obviously relevant information (Boot et al., 2017a, 2017b, 2017c, 2017d; Cropley, 2006). To measure convergent thinking, there are a number of performance tests used in research settings (see Table 1). The most frequently used test is the Remote Associates Task (Mednick & Mednick, 1967), where one is asked to find a fourth word (e.g., cheese) that is related to three other given words that are not otherwise connected (e.g. cottage, swiss, cake). Convergent thinking also entails thinking along a certain line (Boot et al., 2017d). For instance, in the Pasta task, participants are asked to generate as many new pasta names as possible. An implicit rule is cued by providing three example names that follow a certain rule (all example names end with an ‘i’). Participant’s responses are then scored as being rule convergent (number of new names ending with an ‘i’, following the implicit rule given in the instructions), but also rule divergent (number of names not ending with an ‘i’, thus diverging from the implicit rule in the instructions) (Boot et al., 2017b). For more examples of convergent thinking tasks, please see Table 1.

The above-mentioned stratification does, however, require a disclaimer. Although certain tasks predominantly rely on either divergent or on convergent thinking, in most cases they do not exclusively do so. Consider the Remote Associates Task, in which people rely on the activation of associations (e.g., potentially correspondent attributes and relations associated with the three provided words) before they test the correctness of a possible solution through convergent processing (Chermahini and Hommel, 2010; Cortes et al., 2019; De Dreu et al., 2014; Folley and Park, 2005). In addition, many other cognitive processes besides divergent and convergent thinking are important for creative thinking, such as preparation (learning and knowledge), incubation (subconsciously searching for an answer) and productivity (Wallas, 1926). It is important to mention that these processes might also be affected by the ADHD phenotype.

It should also be mentioned that many of these cognitive processes are related to general cognitive functioning and thus to intelligence as well. In fact, the relation between IQ and creativity has been the topic of considerable research and debate (see Silvia, 2015 for a review). Both constructs are highly related, although it also has been found that the correlation between IQ and creativity is only found below a certain IQ threshold (often found at IQ = 120). In other words, intelligence can be regarded as a necessary but not sufficient condition for creativity.

Both divergent thinking and convergent thinking are tested using standardized performance tasks. Another way of assessing creativity is by rating and reporting one’s creative achievements. For instance, using the consensual assessment technique, independent judges with domain-relevant expertise (e.g., in poetry) rate the creativity of the output by creators (e.g., poems; Silvia et al., 2008), or people report concrete creative achievements that are recognized by others in various domains, such as arts, architecture, and science, using the creative achievement questionnaire (CAQ; Carson, et al., 2005). For more tasks see Table 1,

which also shows that several tasks measure more than one aspect of creativity.

Interestingly, divergent thinking, convergent thinking, and creative achievements may be differentially associated with ADHD. For instance, reduced inhibition, known as a hallmark of the ADHD phenotype, may allow a larger range of stimuli to enter working memory, which can be used to create novel and original responses (Kasof, 1997; Zabelina et al., 2016a). However, since convergent thinking requires prolonged sustained attention and goal-directed behavior, this type of creative thinking may be positively related to good inhibitory skills and negatively to distractibility and ADHD (Hommel, 2012; Lucas and Nordgren, 2015). Therefore, this review aimed to provide the field with an overview of the outcomes of studies looking at the association between divergent and convergent thinking, and the ADHD clinical and sub-clinical phenotype.

3. Reviewing behavioral studies investigating the association between ADHD and creativity

To further our understanding of the link between creativity and ADHD, we choose to more specifically review aspects of the published studies that are of interest for ADHD in contrast with the previous meta-analysis (Paek et al). This study had a more global aim of reviewing the relation between psychopathology and creativity. To address this aim we separate clinical case-control studies and population-based ADHD trait studies. This way it becomes possible to examine whether individuals who score high on ADHD symptoms but fail to meet clinical standards of the disorder (e.g. those in healthy population studies) score better on creativity tasks compared to individuals with ADHD symptoms that do meet the criteria for an ADHD diagnosis (e.g. those in case-control studies). This has also been shown for the relationship between bipolar disorder/schizophrenia and creativity measures (Baas et al., 2016). Second, age was included as a moderator in the Paek study, but for a more complete understanding it is necessary to distinguish between childhood studies and adult studies because of the developmental perspective of ADHD and creativity development (Cassotti et al., 2016; Franke et al., 2018; Healey, 2014). Third, a moderator analysis was done for ‘type of creativity assessment’, distinguishing among process, person (creative personality assessments), product (creative achievement measures), and a miscellaneous measurement category. However, there are different creativity-relevant processes (Cropley, 2006; Nijstad et al., 2010) with different neural signatures (Beversdorf, 2019; Boot et al., 2017c; Jauk et al., 2015, Lin & Vartanian, 2018). For ADHD it would be particularly interesting to distinguish between convergent and divergent thinking to better understand the link with symptoms and the underlying neurobiology. Fourth, the effect of medication on creativity was not taken into account. Although methylphenidate, the most frequently used pharmacological treatment in ADHD, has shown positive effects on various cognitive measures (Coghill et al., 2014b), individuals with ADHD often report that their ADHD medication (often stimulants) suppresses their creativity (Brinkman et al., 2012; Kovshoff et al., 2016).

We have conducted our systematic searches of the literature on 5 December 2019 using the pubmed and Web of Science databases (no time restrictions, all databases). The search query was restricted to publications in English and journal articles (no reviews), and consisted of the following keywords and Boolean connectors: 1. TS=(ADHD OR attention deficit hyperactivity disorder) AND (creativ* OR “divergent thinking”); 2. TS=(ADHD OR attention deficit hyperactivity disorder) AND (“convergent thinking”); 3. TS=(ADHD OR attention deficit hyperactivity disorder) AND (creative abilities OR creative achievement); 4. TS=(creativ*) AND (stimulant*). An article was included in our literature review if the reported research 1) had a design that was empirical and quantitative; 2) had a behavioral performance measure that involved a creative process or achievement; 3) reported on human subjects – animal studies were excluded; and 4) included subjects with

an ADHD diagnosis based on assessments made by a professional or including subjects with information about ADHD symptoms using a questionnaire or interview, such as the Adult Self Report Scale (ASRS) or the Conner's Adult ADHD Rating Scales (CAARS). We extracted the following key factors from the selected studies: age group (<18 years are children, whereas respondents older than 18 years constitute adult studies, as most studies use this cutoff), type of sample (clinical case-control sample or population-based sample), sample size, description of ADHD assessment, creativity measure and outcomes of the study.

In order to determine the quality of the studies, we extracted additional information from the selected publications. Based on previous work (Ioannidis et al., 2019) and based on consensus among the study team, we chose the following quality parameters: 1. Appropriate matching of study groups with regard to age, sex and IQ; 2. Type of assessment of ADHD diagnosis/symptoms; 3. Availability of information about comorbid disorders; 4. Sample size of the study. For the studies on the effect of psychostimulants we also looked at the study design (double blind and placebo-controlled). We chose these measures because they are all important for the reliability of the results. These quality scores give us an indication of the current status of the quality of the studies that have been performed so far. These scores will help us to identify opportunities to increase the quality of the studies, which will help to increase the reliability of the results. The procedure for quality scoring is described in Supplementary Table 1. The range of quality scores goes from 0, indicating limited quality for the research, to 5, indicating the highest quality for the research. For the studies on stimulants the range is 0–4. The quality scores were rated by MH, and a subset of the scores (120 observations; 56 %) were rated by MS and MB to determine the inter-rater reliability. The intraclass correlation coefficient was calculated to determine the agreement on the total quality scores.

3.1. Divergent thinking and ADHD

Our systematic search for divergent thinking studies related to ADHD resulted in a final selection of 22 studies. For an overview of the included studies, please see Table 2. A flow chart of the selection process can be found in Supplementary Figure 1.

3.1.1. Case-control studies: children

We found nine studies with a case-control design where the cases were formally diagnosed with ADHD by a trained professional using DSM or ICD criteria reporting on the performance on various divergent thinking tasks (Table 2). In six of those studies, the figural test of the Torrance Test of Creative Thinking (TTCT) (Torrance, 1962) was used (Aliabadi et al., 2016; Funk et al., 1993; Healey and Rucklidge, 2005, Healey & Aucklidge, 2006a&b; Healey and Rucklidge, 2008;), three studies used the alternative uses task (Abraham et al., 2006; Ludya et al., 2018; Solanto and Wender, 1989). Other tasks that were used included the conceptual expansion task, the recently activated knowledge task, and the instances test (Abraham et al., 2006; Solanto and Wender, 1989). Of the nine case-control studies, seven studies showed no positive association between any of the features of divergent thinking and ADHD, i.e., the ADHD group did not score significantly higher on divergent thinking tasks as compared with controls. Two studies of those seven studies even show a negative association between ADHD and divergent thinking, more specifically on fluency and flexibility (Aliabadi et al., 2016) and on a combined score of fluency, flexibility and originality (Funk et al., 1993). One of the positive results came from a study using the recently activated knowledge task (Abraham et al., 2006). This task differs from the other tasks in that it asks subjects to draw a new and different toy after being shown three examples that have three features in common. The new toys are coded for whether they included these three features. This means that there is also an implicit cue that demands convergent thinking. The other positive result was shown in a study using the figural-TTCT but here only increased scores on elaboration were found for individuals with ADHD, whereas the scores on the other

features of divergent thinking did not differ between cases and controls (Healey and Rucklidge, 2005).

In four other studies researchers did not use a formal diagnosis of ADHD, using instead an ADHD self-rating scale (Fugate et al., 2013) or teacher rating scale (Shaw et al., 1990, 1991 & 1992) to assess ADHD symptoms and accordingly defining an ADHD group and a non-ADHD group. Given the similarity in design, i.e. comparing two groups, we also report on those studies here. One study among gifted children showed that the children with high ratings of ADHD symptoms outperformed those scoring low on ADHD on elaboration and abstractness of titles of the figural form of the TTCT (Fugate et al., 2013). Geraline Shaw published three studies, with the third study being a combination of the first two studies. In these studies, teachers used the Conner's Abbreviated Teacher Rating Scale to rate ADHD symptoms in a group of above-average intelligent children (IQ > 115). The ADHD group was defined as the group with the 15 % highest scores on the Conner's scale and, to compose a control group, were matched on age, gender and IQ with the 50 % lowest-scoring children (Shaw, 1992; Shaw and Brown, 1990, 1991). In all three studies higher scores were found for the ADHD group as compared with the control group with respect to the figural TTCT as well as to all features of divergent thinking.

One study had a different design and measured how many individuals in a group of children with an ADHD diagnosis scored above the 90th percentile of scores on the TTCT figural form A. In addition, they assessed the incidence of individuals with behaviors indicative of ADHD (using self- and teacher ratings) in a group of highly creative individuals, i.e. scoring above the 90th percentile of the TTCT (Cramond, 1994). In the ADHD group, 30 % scored above the TTCT cutoff. This is higher than the expected 10 % that would score above the 90th percentile. The researchers also found a higher incidence of individuals with ADHD behavior in the highly creative group than would be expected on the basis of ADHD prevalence rates in the general population.

In summary, with two exceptions showing enhanced divergent thinking in the formally diagnosed ADHD group, all studies comparing children with and without an ADHD diagnosis on divergent thinking task performance showed either worse performance or no difference. Although these two exceptions fall in the category divergent thinking, these two results relate to different features of divergent thinking (elaboration and a mixed component of divergent and convergent thinking). A different pattern is seen in studies stratifying individuals based on their self- or teacher-rated ADHD symptom score (high versus low). It should be noted that most of these studies were conducted with highly intelligent children, where we see a positive association between divergent thinking and ADHD with no preference for any specific feature of divergent thinking. This underpins the idea that creativity might indeed be associated with ADHD (symptoms) but not in people diagnosed with the disorder, as these people might be too constrained by additional cognitive deficits; though it should probably be formulated in reverse: only people with high intelligence show extra creativity because of their additional cognitive strengths.

3.1.2. Case-control studies: adults

There are five studies (Table 2) that report on possible differences in divergent thinking between formally diagnosed adults with ADHD and a control group. Two studies did not find any positive association between ADHD and divergent thinking (Barkley et al., 1996a; Boot et al., 2017a), while three studies did (White and Shah, 2006, 2011, 2016). However, it should be noted that a variety of tasks were used in the studies, which compromises a straightforward comparison. The two studies that did not find a positive association used the Unusual Uses Task and the Spatial Creativity Task (Barkley et al., 1996a) and the alternative uses and problem construction tasks (Boot et al., 2017a). Interestingly, in this latter study, extrinsic motivators did help individuals with ADHD to become more creative. Different results were found in a series of studies from White and Shah. Subjects with ADHD scored higher on fluency, flexibility and originality of the Unusual Uses task (White and Shah,

Table 2
Overview of studies reporting divergent thinking tasks and the association with ADHD diagnosis or ADHD symptoms.

Author	Category	Sample size	ADHD variable used in creativity analysis	Creativity Measure	Outcome	ADHD positively associated with creativity?
Abraham et al., 2006	Children, Case-control	N = 44 –11 ADHD –12 Conduct disorder	ADHD versus control status. ADHD cases were diagnosed prior to study by chief consultant psychiatrist from a local Child and Adolescent psychiatry unit, using DSM-IV criteria. Controls were age and IQ matched and recruited via newspaper advertisements.	- Ward animal task - Recently activated knowledge task - AUT (fluency and originality)	- No difference on Ward animal task (conceptual expansion). - Better performance on the recently activated knowledge task (ADHD group was less constrained by the examples). - No differences on fluency and originality of the AUT.	yes and no
Aliabadi et al., 2016	Children, case-control	N = 66 –33 with ADHD –33 controls	ADHD versus control status. The ADHD group consisted of children recruited from a psychiatry clinic and who met the DSM-IV-TR criteria for ADHD.	TTCT-figural (total, fluency, elaboration, originality, flexibility)	- No differences on total creativity score, originality and elaboration. - Children with ADHD performed significantly worse on fluency and flexibility.	No
Funk et al., 1993	Children, case-control	N = 40 –19 with ADHD –21 controls	ADHD versus control status. ADHD cases were previously diagnosed by physician or multidisciplinary team and had current elevations in Conners Hyperactivity Index score by parent report. Controls did not meet those criteria.	TTCT-figural (creativity index, a combined score of all subtests)	- ADHD had significant lower mean scores on the creativity index compared to controls.	No
Healey and Rucklidge, 2005	Children, Case-control	N = 67 –33 ADHD –34 controls	ADHD versus control status. The ADHD group was established by confirming that each child was diagnosed with ADHD by a psychiatrist or registered psychologist. In addition, current t-scores of 65 or higher on the DSM-IV Inattentive, DSM-IV Hyperactive-Impulsive, and/or DSM-IV Total subscales of the long versions of the parent and teacher forms of the Conners' Rating. Controls had t-scores <65 on the Conners' Rating.	TTCT-figural (Originality, Fluency, Elaboration, Abstractness of Titles, and Resistance to Premature Closure)	- No significant differences between the groups on all measures of the TTCT, except for elaboration. Children with ADHD scored lower on elaboration.	Yes (elaboration) and No
Healey and Rucklidge, 2006a	Children, Case-control	N = 89 –29 ADHD with normal creativity –12 ADHD with high creativity –18 High creativity without ADHD –30 controls	ADHD versus control status and ADHD symptoms rated by parents. All children in the ADHD group had received a prior diagnosis of ADHD from either a psychiatrist or registered psychologist before entering the study. T-scores of 65 or above on the DSM-IV inattentive, DSM IV hyperactive-impulsive, and/or DSM IV total subscales of the long versions of the parent form of the Conners' Rating Scales-Revised were used to confirm ADHD diagnosis.	TTCT-figural (percentile ranking of combined scores of originality, fluency, elaboration, abstractness of titles, and resistance to premature closure)	- the high creativity group with ADHD and high creativity without ADHD group scored better than the ADHD and control groups. There were no differences in the creative abilities of the ADHD and control groups –40% of the 30 creative children displayed ADHD symptomatology, but none met full criteria for ADHD.	No for the case-control analysis (but yes for ADHD symptoms)
Healey and Rucklidge, 2006b	Children, Case-control	N = 93 –29 ADHD with normal creativity –16 ADHD with high creativity –18 High creativity without ADHD –30 controls	See Healey 2006a	TTCT-figural (percentile ranking of combined scores of originality, fluency, elaboration, abstractness of titles, and resistance to premature closure)	The results are similar to Healey 2006a. The aim of Healey 2006b was to determine the association between creativity, ADHD symptomatology, temperament and psychosocial functioning.	No
Healey and Rucklidge, 2008	Children, Case-control	N = 67 –33 ADHD –34 controls	ADHD versus control status. Diagnosed with ADHD by psychiatrist or registered psychologist. Controls had no indication of ADHD using the CAARS parent and teacher version.	TTCT-figural (percentile ranking of combined scores of originality, fluency, elaboration, abstractness of titles, and resistance to premature closure)	No significant differences were found between the ADHD and control groups for the total score on the TTCT	No
Ludyga, Gerber, Mücke, Brand,		N = 36 –18 ADHD	ADHD versus control status. The ADHD group consisted of			No

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Table 2 (continued)

Author	Category	Sample size	ADHD variable used in creativity analysis	Creativity Measure	Outcome	ADHD positively associated with creativity?
Weber, Brotzmann & Pühse, 2018	Children, Case-control	-18 controls	children who met the diagnostic criteria of ADHD-combined type according to the DSM-V recruited from pediatricians.	AUT (fluency, flexibility, originality, and elaboration)	there was no significant difference between groups on AUT scores	
Solanto and Wender, 1989	Children, case-control	N = 37 -19 ADHD -18 control	ADHD versus control status. DSM-III diagnosis of ADD with hyperactivity assigned independently by both the psychologist and pediatrician.	Wallach-Kogan Tests: AUT (fluency, functionality, classes, unintended uses, and classes among unintended uses) & Instances Test	No significant differences between the ADHD group and the normal controls.	No
Cramond, 1994	Children, different design	N = 110 -34 with ADHD -76 highly creative	Percentage of highly creative in ADHD group versus the reverse. Children in the ADHD group had received an ADHD diagnosis prior to participation and SNAP (based on DMS-III) teacher scores were used to confirm diagnosis.	TTCT-figural (percentile scores for the total score and subscores)	-33% of the ADHD group scored above the 90 th percentile of the TTCT -26% of highly creative group met the criteria for ADHD (teacher SNAP). -on elaboration the ADHD group scored more than one standard deviation above the test mean - Gifted students with characteristics of ADHD had greater creative potential than those without ADHD. - ADHD group scored higher on elaboration and abstractness of titles.	Yes (elaboration and total score)
Fugate et al., 2013	Children, different design	N = 37 -17 gifted children with ADHD characteristics -20 gifted children without ADHD characteristics	Gifted student with versus without ADHD characteristics. ADHD characteristics measured by CASS-S, self-rate questionnaire. Identified ADHD symptoms if t-score was higher than 60 on Inattentive-Passive and/or ADHD index. Without ADHD if T-scores were below 50 on those scales. Else exclusion.	TTCT-figural (creativity Index based on combined scores of originality, fluency, elaboration, abstractness of titles, and resistance to premature closure, subscores were also analyzed)	-41% of the gifted group with ADHD scored at or above the 90 th percentile on the creativity index score. - The combination of inattentiveness and hyperactivity contributes to creativity. This came from the positive correlation reported in this study between the ADHD Index and the Creativity Index, suggesting that inattention and hyperactivity combined may contribute to creativity more than inattention alone. - Children with ADHD characteristics were better at figural creativity (flexibility and originality and total score) than controls.	Yes (elaboration, abstractness of titles, and total score)
Shaw and Brown, 1990	Children, different design	N = 32 -16 Experimental ADHD group -16 controls	Experimental ADHD group versus controls. No official diagnosis, based on teacher and school psychologist, children who were above average in intelligence and who exhibited attentional deficits with hyperactivity.	- TTCT-figural (circles) and verbal (just suppose) both tasks were scored on fluency, flexibility and originality	- No differences on verbal creativity.	yes (flexibility, originality and total score) and no
Shaw and Brown, 1991	Children, different design	N = 32 -16 children with ADHD characteristics -16 controls	Highly intelligent children with (top 15 %) versus without ADHD characteristics (bottom 50 %). ADHD characteristics were based on the Conners Abbreviated Teacher Rating Scale. Multiple teachers filled out the scale ADHD group consisted of the top 15 % of the distribution on this scale.	- TTCT-figural (circles) and verbal (just suppose) both tasks were scored on fluency, flexibility and originality	- Group of children with ADHD characteristics achieved higher scores on the fluency, originality and total scores on the figural creativity test.	Yes (fluency, originality, total score)
Shaw, 1992	Children, different design	Combined data; Shaw 1990 & Shaw 1991 -32 ADHD group -32 controls N = 48 -25 ADHD	See Shaw, 1990&1991	- TTCT-figural (circles) and verbal (just suppose) both tasks were scored on fluency, flexibility and originality	Total scores on the figural creativity task were higher in the ADHD group.	Yes (combined score)
Barkley et al., 1996a	Adults, case-control	-23 controls	ADHD versus control status. The ADHD group received a diagnosis of ADHD at the clinic based on DSM-IV. ADHD symptoms were evaluated using a self-rating rating scale of the 18 items from the DSM-IV.	- Unusual Uses Task (brick, bucket, string; scored on fluency). - Spatial creativity task	No significant differences were found on creativity scores between groups.	No

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Table 2 (continued)

Author	Category	Sample size	ADHD variable used in creativity analysis	Creativity Measure	Outcome	ADHD positively associated with creativity?
Boot et al., 2017a	Adults, case-control	N = 107 –71 ADHD –36 controls	ADHD versus control status and self-reported ADHD symptoms DSM-IV. All participants had been diagnosed by a clinical psychologist or psychiatrist ADHD versus control status.	- AUT (fluency, flexibility, and originality) - Problem construction task	- No differences on fluency, flexibility or originality of the AUT between groups - ADHD group produced less useful problem definitions in the problem construction task	No
White and Shah, 2006	Adults, case-control	N = 90 –45 ADHD –45 controls	The ADHD group had a prior diagnosis of ADHD-combined type by clinician and qualified for inclusion on the basis of two self-report assessment measures.	Unusual Uses task (combined score of fluency, flexibility, and originality)	ADHD group performed better on all components of the UUT	Yes (fluency, flexibility, originality)
White and Shah, 2011	Adults, case-control	N = 60 –30 ADHD –30 Non-ADHD N = 60	ADHD versus control status. The ADHD group had a prior diagnosis of ADHD-combined type by clinician and qualified for inclusion on the basis of two self-report assessment measures.	ATTA (figural and verbal fluency, flexibility, originality, and elaboration)	- ADHD group did not differ from non-ADHD group on ATTA, however if a distinction is made between verbal and figural task: Higher Verbal Originality for ADHD. -Groups did not differ on Verbal Fluency, or Figural Fluency and Originality.	Yes (originality) and no
White and Shah, 2016	Adults, case-control	–30 ADHD	ADHD versus control status.	- Cell phone task (invent many new features) - Word associations task (measures semantic distance)	- multivariate effect of case-control status was not statistically significant - Analysis of between subjects effects revealed that the ADHD group scored higher in flexibility, novelty and originality. No differences in fluency, switching, elaboration and appropriateness. - The ADHD group had greater semantic distances compared to the non-ADHD group. -Flexibility was mediated by semantic distance (novelty and originality not). This may be attributable to diffuse semantic activation associated with ADHD.	Yes (flexibility, novelty and originality) and no
Brandau, Daghofer, Hollerer, Kaschnitz, Kellner, Kirchmair, ... Schlagbauer, 2007	Children, population	N = 71 –30 controls	The ADHD group had a prior diagnosis of ADHD-combined type by clinician and qualified for inclusion on the basis of two self-report assessment measures. - Conners abbreviated teacher rating scale	-Teacher rating questionnaire based on the DSM IV criteria. Creativity test for preschoolers and pupils (fluency and flexibility). - Problem construction task - Pasta task	- Children who score low on inattention symptoms have high scores on flexibility - higher scores on Conners teacher rating scale were associated with higher score on fluency - ADHD symptoms are associated with enhanced divergent thinking. Mainly driven by hyperactive-impulsive ADHD symptoms	No and yes (fluency)
Boot et al., 2017b	Adults, Population	Study 1: n = 419 Study 2: n = 649 Study 3: n = 205	Self-reported ADHD DSM-IV rating scale for adults (Kooij, 2015)	- AUT (fluency, flexibility, and originality)	- More original but less practical reconstruction of complex problems - Inattention symptoms predicted enhanced divergent thinking on one of the creative ideation tasks, but reduced	Yes (originality)

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Table 2 (continued)

Author	Category	Sample size	ADHD variable used in creativity analysis	Creativity Measure	Outcome	ADHD positively associated with creativity?
Zabelina et al., 2014		Adults, population	N = 100	Adult ADHD Self-Report Scale (ASRS)	usefulness of problem construction. ATTA (combined score of fluency and originality and consensual assessment technique)	ADHD questionnaire did not predict divergent thinking.
No						

Abbreviations: TTCT= Torrance Tests of Creative Thinking; AUT= Alternative Uses Task, ATTA= Abbreviated Torrance Tests for Adults.

2006), higher on verbal originality in the Abbreviated Torrance test for Adults (White and Shah, 2011), and higher on flexibility, novelty and originality in the Cell Phone Task (White and Shah, 2016). No differences were found for the subscales verbal fluency and figural fluency and the originality of the Abbreviated Torrance Test for Adults and also no differences were found for fluency, switching, elaboration, and appropriateness on the Cell Phone Task (White and Shah, 2011, 2016).

In sum, the results of the adult ADHD studies are mixed. Some studies show that individuals with ADHD perform better than controls, most consistently on originality, but other studies report null effects. There were indications that motivational factors might play a role in explaining this discrepancy.

3.1.3. Self or teacher rated ADHD symptoms in the population: children and adults

Symptoms of inattention, hyperactivity and impulsivity can be viewed as a continuum in the population, with the clinical diagnosis of ADHD at the end of this continuum. There is enough evidence to support the notion that ADHD symptoms in a population sample (almost always measured using self-report questionnaires) represent the same construct as the ADHD diagnosis, to be viewed as the upper extreme of the distribution. This evidence comes from neurocognitive research (Salum et al., 2014), from genetic research (Stergiakouli et al., 2015; Middeldorp et al., 2016 & Demontis et al., 2019), and also from neuroimaging research (Hoogman et al., 2019). The degree of symptoms in the general population can therefore be used to learn more about ADHD and its relation with creativity. Three studies have been published on the relation between ADHD symptoms and divergent thinking. The first study investigated the association between teacher rated ADHD symptoms and creativity in a child sample. They showed that more impulsive/hyperactive symptoms using the CAARS teacher scale was related to better performance on fluency. This study also showed that children who scored low on inattention had a better performance on flexibility, using the Creativity Test for Preschoolers and Pupils (Brandau et al., 2007). The second study on ADHD symptoms and divergent thinking investigated the association between creative abilities and specific self-reported symptoms of ADHD in three independent student samples (Boot et al., 2017b). They found the number of hyperactivity and impulsivity symptoms to be positively associated with performance on the divergent thinking aspect of the Pasta Task and measures of the Alternative Uses Task. More specifically, these symptoms were associated with more original but less practical ideas. Inattention symptoms were not related to divergent thinking measures. The third population based study on self-reported ADHD symptoms and divergent thinking showed no association between ADHD symptoms and performance on the Abbreviated Torrance Test for Adults (Zabelina et al., 2014).

In conclusion, the relation between divergent thinking and ADHD is far from clear. Although we do not have an abundance of studies to draw conclusions from, in children there seems to be a distinction between children with a formal ADHD diagnosis (that do not show increased divergent thinking abilities) and children with high numbers of teacher-rated ADHD symptoms (that do show increased divergent thinking

abilities). In accordance, when considering the study in adults with the highest statistical power, similar evidence was found that people with more self-reported ADHD symptoms (especially hyperactive impulsive symptoms) have increased divergent thinking abilities (Boot et al., 2017b). This points to an interesting phenomenon that should be investigated further to fully understand how ADHD and creativity are linked. The ideal set up for future studies would be to include large population and clinical samples and administer the same divergent thinking task (or a divergent thinking test battery). This way the entire continuum of ADHD symptoms can be mapped for its association with divergent thinking. Such a design makes it possible to answer the question whether there is indeed a 'bump' in divergent thinking scores for people with an increased number of ADHD symptoms but not for those with too many ADHD symptoms that also have the disorder, where related deficits might weaken the association. In addition, a clinical study with both creativity measures and measures of known cognitive deficits in ADHD gives the possibility to find out if and how ADHD deficits are related to divergent thinking. It would also be interesting to further investigate what the role of IQ is, because it could be the case that a certain level of intelligence is needed to be creative (threshold hypothesis; Guilford, 1967; Jauk et al., 2013) especially for people with ADHD. Finally, there is not one specific feature of divergent thinking that stands out in its relationship with ADHD, although four of seven among the adult studies (three case-control and one population-based) report increased originality scores in relation to ADHD.

3.2. Convergent thinking and ADHD

Table 3 shows an overview of included studies testing the link between convergent thinking and ADHD. For a complete overview of our search, see the flowchart in Supplementary Figure 2. Our systematic search for convergent thinking studies in ADHD resulted in a final selection of six studies.

3.2.1. Case-control studies: children and adults

Three studies from the same research group used the Maier's two string problem task (Maier, 1931) to assess convergent thinking in three studies with a child sample. In this task two strings are hanging from the ceiling and need to be tied together, but when holding one string, the person could not reach the other. Tools such as a scissor, are available and participants have to come up with a solution. In none of these studies did formally diagnosed ADHD cases differ from healthy controls on the outcome of this task (Healey and Rucklidge, 2008, 2005, 2006a). On the creative imagery task, where participants have to recombine familiar shapes into an invention that falls into a predefined category, children with an ADHD diagnosis had lower scores on the practicality dimension (a rating of how functional and usable the invention is) when compared with controls (Abraham et al., 2006). In addition, one other patient study was published that examined diagnosed adults with ADHD and healthy controls by using the Remote Associations Task. Here, individuals with ADHD had lower scores on this task compared to healthy controls (White and Shah, 2006). Moreover, additional analysis showed

Table 3

Overview of studies reporting convergent thinking tasks and the association with ADHD diagnosis or ADHD symptoms.

Study	Categorie	Sample size	ADHD variable used in creativity analysis	Creativity measure	Outcome	ADHD positively associated with creativity?
Abraham et al., 2006	Children, Case-control	N = 44 –11 ADHD –12 Conduct disorder –21 Control group N = 67 –33 ADHD	ADHD versus control status. ADHD cases were diagnosed prior to study by chief consultant psychiatrist from a local Child and Adolescent psychiatry unit, using DSM-IV criteria. Controls were age and IQ matched and recruited via newspaper advertisements. ADHD versus control status. The ADHD group was established by confirming that each child was diagnosed with ADHD by a psychiatrist or registered psychologist.	Creative imagery task	ADHD group performed worse on practicality dimension	No
Healey and Rucklidge, 2005	Children, Case-control	–34 controls	In addition, current t-scores of 65 or higher on the DSM-IV Inattentive, DSM-IV Hyperactive-Impulsive, and/or DSM-IV Total subscales of the long versions of the parent and teacher forms of the Conners' Rating. Controls had t-scores <65 on the Conners' Rating.	Maier's Two string problem	No difference between the ADHD and control group was found	No
Healey and Rucklidge, 2006a	Children, Case-control	N = 89 –29 ADHD with normal creativity –12 ADHD with high creativity –18 High creativity without ADHD –30 controls	ADHD versus control status and ADHD symptoms rated by parents. All children in the ADHD group had received a prior diagnosis of ADHD from either a psychiatrist or registered psychologist before entering the study. T-scores of 65 or above on the DSM-IV inattentive, DSM IV hyperactive-impulsive, and/or DSM IV total subscales of the long versions of the parent form of the Conners' Rating	Maier's Two string problem	No difference between the ADHD group and the control group was found	No
Healey and Rucklidge, 2008	Children, Case-control	N = 67 –33 ADHD –34 controls	Scales-Revised were used to confirm ADHD diagnosis. ADHD versus control status. Diagnosed with ADHD by psychiatrist or registered psychologist. Controls had no indication of ADHD using the CAARS parent and teacher version.	Maier's Two string problem	No difference between the ADHD group and the control group was found	No
White and Shah, 2006	Adults, case-control	N = 90 –45 ADHD –45 controls	ADHD versus control status. The ADHD group had a prior diagnosis of ADHD-combined type by clinician and qualified for inclusion on the basis of two self-report assessment measures.	Remote associations task (proportion correct score)	The ADHD group performed worse on RAT than the control group	No
Boot et al., 2017b	Adults, population	Study 1: n = 419 Study 2: n = 649 Study 3: n = 205	Self-reported ADHD DSM-IV rating scale for adults (Kooij, 2015)	Remote associations task (proportion correct score) & Pasta task	Hyperactive-impulsive symptoms negatively predicted RAT performance Both hyperactivity-impulsivity and inattentions subscale did not correlate with convergent thinking on the Pasta Task.	No

that performance on the Remote Associations Task was mediated by inhibitory control.

3.2.2. Self-reported ADHD symptoms in the population: children and adults

In children, no studies on the association between self-reported ADHD symptoms and convergent thinking have been published. However, a large adult population study did report on the relation between self-reported ADHD symptoms and convergent thinking (Boot et al., 2017b). In this study, convergent thinking was measured with the Pasta task (De Dreu et al., 2014) and with the remote associations task. They showed that self-reported ADHD symptoms in general, and symptoms of hyperactivity and impulsivity specifically, negatively predicted performance on the remote associations task. Symptoms of inattention did not predict convergent thinking. No associations between self-reported ADHD symptoms and convergent thinking subscores of the Pasta task were observed.

To summarize, the six studies investigating convergent thinking and the association with self-reported ADHD symptoms showed three child studies with null effects, and one child and two adult studies with

negative effects. On the basis of these findings we cannot assume that individuals with ADHD, or those with high rates of self-reported ADHD symptoms, have increased convergent thinking abilities. In studies where the RAT was used, only the proportion correct score was analyzed. It could deliver valuable additional information about the null-findings, if, like in the Compound Remote Associates Task, participants were whether they used insight or analysis to come up with their answer.

3.3. Creative abilities and achievements

The included studies for the link between creative abilities \achievements and ADHD are listed in Table 4. For a complete overview of our search results, please see the flowchart in Supplementary Figure 3.

3.3.1. Case-control studies: children and adults

No case-control studies of children with a formal ADHD diagnosis using creative ability or achievement measures appeared in our

Table 4

Overview of studies reporting creative abilities/achievements and the association with ADHD diagnosis or ADHD symptoms.

Study	Category	Sample size	ADHD variable used in creativity analysis	Creativity measure	Outcome	ADHD positively associated with creativity?
Boot et al., 2017a	Adults, Case control	N = 107 –71 ADHD –36 controls	ADHD versus control status and self-reported ADHD symptoms DSM-IV. All participants had been diagnosed by a clinical psychologist or psychiatrist	Creative Achievement Questionnaire	In the ADHD group more real-world creative achievements were reported compared to the healthy controls.	yes
DuPaul et al., 2017	Adults, Case-control	N = 15.273 first-time, full-time first-year students 5511 reported having ADHD 2626 reported having Learning disabilities 1399 both 5737 controls	ADHD versus control group. The ADHD group was defined as those students who indicated they had ADHD but no other disorders.	Creative self-reports (e.g. academic ability, writing ability) = based on 2 items.	Main effect of group was significant for creative self-ratings. Those in the ADHD group self-reported higher creativity than all other groups	yes
Kyaga, Landén, Boman, Hultman, Långström & Lichtenstein, 2013	Adults, Case control	N = 1.173.763 –48.024 ADHD –1.125.739 others	ADHD versus all others. The ADHD group consisted of subjects who had received an ADHD diagnosis based on ICD 8, 9 and 10 in the part (national registries)	Creative occupations	Individuals holding creative professions had a significantly reduced likelihood of being diagnosed with ADHD.	no
White and Shah, 2011	Adults, Case-control	N = 60 –30 ADHD –30 Non-ADHD	ADHD versus control status. The ADHD group had a prior diagnosis of ADHD-combined type by clinician and qualified for inclusion on the basis of two self-report assessment measures.	Creative Achievement Questionnaire	Higher overall creative achievement in the ADHD group compared with the Non-ADHD group.	yes
Boot et al., 2017b	Adults, population	Study 1: n = 419 Study 2: n = 649 Study 3: n = 205	Self-reported ADHD DSM-IV rating scale for adults (Kooij, 2015)	- Creative Behavior Scale - Creative Achievement Questionnaire	The meta-analysis of the three studies showed: ADHD symptoms correlated positively with creative achievement and self-reported creative behavior. Creative achievement was significantly correlated with ADHD. Not significant after controlling for academic achievement scores.	yes
Zabelina et al., 2014	Adults, Population	N = 100	Adult ADHD Self-Report Scale	Creative Achievement Questionnaire		Yes/no

literature search, but four studies that included adults with ADHD were found. Three of those four studies reported a positive association between ADHD and creative achievements (Boot et al., 2017a; DuPaul et al., 2017; White and Shah, 2011). These studies report a higher rate of creative achievements in daily life for adults diagnosed with ADHD compared to controls (Boot et al., 2017a; White and Shah, 2011). Boot and colleagues further explain this result by reporting that adults with ADHD are more strongly triggered by rewards, which may lead to more creative achievements through increased effort. In another study, college students were grouped based on self-reported ADHD diagnosis, which could mean that there might be individuals who self-diagnosed their ADHD or that due to their (hyper)active behavior they were told by their parents or peers that they might have ADHD. These could be people with a high number of ADHD symptoms but without the deficits that come with the disorder and are therefore not true cases. Nonetheless, the ADHD group of that study reported more creative abilities than the group that did not report having ADHD (DuPaul et al., 2017), and those who reported having ADHD and learning difficulties indicated significantly lower creative abilities compared to those with ADHD alone. The fourth study involving adults did not show an association between creativity and ADHD diagnosis but used a different approach. The largest prospective study, using the Scandinavian registries, researched everyday creativity in individuals with an ADHD diagnosis versus those without. They found that the likelihood of an ADHD diagnosis decreased in the group of individuals who ever had a creative

job (Kyaga et al., 2013). Creative jobs were defined as ‘scientist, visual artist, photographer, designer, display artist, performing artist, composer or musician, choreographer/dancer, author or other literary and artistic work’. A limitation of this study is that this categorization is arbitrary and creativity can be part of any job. Interestingly, results did suggest a relation between creative professions and ADHD among the children of individuals with ADHD.

3.3.2. Self-reported ADHD symptoms in the population: adults

Contradicting results are reported in the two studies using a population-based design to assess the association between creative achievements and self-reported ADHD symptoms. Zabelina and co-workers reported a significant positive correlation between creative achievement scores and number of self-reported ADHD symptoms, however, this effect disappeared after controlling for academic achievement (Zabelina et al., 2014), and when correction for multiple comparisons was applied. However, in the study by Boot and colleagues, self-reported symptoms of ADHD were positively correlated with creative achievements in daily life and with a self-report measure of creative behavior. When zooming in on the specific symptom domains, hyperactivity/impulsivity symptoms were the main drivers of the effect (Boot et al., 2017b).

To conclude, since the proposed link between creativity and ADHD comes from patient reports (Sedgwick et al., 2018) and anecdotal evidence, it would seem plausible that measures of little-c (personal,

everyday) creativity and creative achievements are especially correlated with an ADHD diagnosis. Reviewing the current literature, four of six studies investigating creative achievements and ADHD showed a positive correlation, including two well-powered studies (Boot et al., 2017b; DuPaul et al., 2017). The big exception comes from a large study with a different way of looking at creative achievement: using creative professions as a proxy for daily life creativity/creative achievement. The findings of this study, however, should be treated with caution. First, unemployment rates among individuals with ADHD are high (Fleming et al., 2017; Klein et al., 2012). Second, the question whether a job is creative is arbitrary. Many of the jobs, such as writers and scientists, are certainly in domains that are commonly associated with creativity, but other creative domains such as cooking and architecture were not covered. Furthermore, creative feats are possible in every domain, from accountancy and teaching to carpentry and plumbing. This relates to a

more general point that the level of creativity in any job is more relevant, but this was not assessed. Despite all this, the suggestion that the children of those with an ADHD diagnosis are more likely to have a creative profession is interesting evidence and is also in line with previous work showing that psychopathologies are still present today because their milder versions can be beneficial (Nettle, 2006; O'Reilly et al., 2001).

It must be noted that, similar to our review about ADHD and convergent thinking, the field is immature; only a few studies have been performed on this particular subject. Rethinking the research format for how ADHD relates to creative professions will generate a more powerful design that will deliver more information about the link between ADHD and creativity and how it translates to daily life. For example, we should not only be looking at the creative professions as a dichotomous variable, but also at the level of creativity of persons both in creative

Table 5
Overview of studies reporting effects of psychostimulants on creativity measures.

Author	Sample	Design	Creativity task	outcome	MPH versus No-MPH
Baas et al., 2019	–48 healthy adults	Randomized, double-blind cross-over (2 sessions, placebo & MPH)	AUT, RAT, ANT	MPH did not affect any of the creativity measures	Convergent:= Divergent:=
Boot et al., 2017a	–71 adult with ADHD (42 medicated and 29 non medicated)	Comparing cases with and without medication	AUT, Problem construction task, CAQ	No differences between medicated and unmedicated participants with ADHD on any of the tasks.	Divergent:= Convergent:= Daily life:=
Douglas et al., 1995	–17 children with ADHD	Randomized, cross-over, double blind (8 sessions, 2 times: 1 placebo and 3 doses of MPH)	AUT and Instances test	On the AUT more responses and categories were reported with increasing MPH dose. no effect on the instances test.	Divergent:=
Farah et al., 2009	–16 healthy adults	Double blind, cross-over placebo-Adderall (2 sessions)	2 divergent (AUT and drawing from ATTA) 2 convergent (group embedded figures and Remote associations)	Adderall affected performance on the convergent tasks only, in one case enhancing it, particularly for lower-performing individuals, and in the other case enhancing it for the lower-performing and impairing it for higher-performing individuals. No effects of Adderall on divergent thinking tasks.	Convergent:+/ Divergent:=
Funk et al., 1993	–19 children with ADHD –21 control children	Cross-over (once with normal dose and once off medication, controls only off medication)	TTCT-Figural	methylphenidate did not influence performance on TTCT	Divergent:=
Gonzalez-Carpio Hernández & Serrano Selva, 2016	–24 children with ADHD	Randomly assigned to one of the two groups: 1.children were assessed before treatment with methylphenidate and again after methylphenidate treatment began. 2. children were assessed while being treated with methylphenidate and then after drug withdrawal.	TTCT-Figural	Higher scores for Creative Index, Fluency, Originality, and Creative Strengths, off medication compared with on medication.	Divergent: -
Gvirts, Maysseles, Segev, Lewis, Feffer, Barnea, ... Shamay-Tsoory, 2017	–36 healthy adults	Randomized, double blind, cross-over (2 sessions: placebo & MPH)	AUT, the circles/ lines subsets of the figural TTCT, lexical fluency task.	No main effects of MPH on the tasks (they did find an interaction with novelty seeking)	Divergent: =
Ilieva et al., 2013	–46 healthy adults	Randomized, double-blind cross-over (3 sessions: baseline, placebo, Adderall)	Embedded figures test and the RAT	No effects of Adderall on convergent thinking tasks.	Convergent:=
Sam, Beversdorf & Ferguson, (2020)	–17 adults with ADHD	Participants were tested once on their current medication and once off their medication	anagrams, compound remote associates, Verbal-TTCT	MPH did not impair creativity in individuals with ADHD	Convergent:= Divergent:=
Solanto and Wender, 1989	–19 children with ADHD –18 control children	Randomized, cross-over, double blind (6 sessions only for ADHD: baseline, 2x placebo and 3 doses of MPH)	Wallach-Kogan battery (AUT and instances test)	increase in performance on the divergent thinking task (AUT & instances test)	Divergent:+
Swartwood et al., 2003	–8 children with ADHD	Cross-over (on and off MPH)	Test of Divergent Thinking	The Elaboration subscale of the TDT was the only scale to show a significant decrease in scores with MPH administration.	Divergent:-/=
White and Shah, 2011	–30 adults with ADHD (15 medicated and 15 non medicated)	Comparing cases with and without medication	CAQ, ATTA	No differences between the treated and non-treated group	Divergent: = Daily life creativity: =

Notes: '='no effects', '+'positive effect of psychostimulants on creativity measure', '-'negative effect of psychostimulants on creativity measure'.

Abbreviations: CAQ = Creative Achievement Questionnaire, ANT = Alternative Naming Task, RAT = Remote Associations Task, AUT = Alternative Uses Task, TTCT = Torrance Tests of Creative Thinking.

professions and professions that are not habitually associated with creativity.

3.4. Effect of psychostimulant use on divergent and convergent thinking as well as on creative abilities/achievements

We retrieved twelve studies that investigated the effect of psychostimulant medication relevant for ADHD on creativity. These can be found in Table 5; please see the flowchart of the selection process on Supplementary Figure 4. There are eight studies of subjects with ADHD – six on children and two in adults. The two studies on children and one on adults (Sam et al., 2020) used a cross-over design, testing patients twice (on and off medication). The other adult studies compared patients who were on medication with patients who were not. The studies of healthy subjects assessed subjects both on and off medication. In one of these studies, ADHD symptoms were measured (Baas et al., 2019). We have included these non-ADHD studies because they contribute to our understanding of the mechanism of the effects of psychostimulants on creativity.

Most of the patient studies (six out of eight) found no effect of methylphenidate on divergent, convergent thinking, nor on creative abilities/achievements (Boot et al., 2017a; Douglas et al., 1995; Funk et al., 1993; González-Carpio Hernández and Serrano Selva, 2016; Sam et al., 2020; Swartwood et al., 2003; White and Shah, 2011). For the two studies that found an effect of stimulant medication on creativity, both a positive and a negative effect on creativity was found. Children with ADHD performed better on the alternative uses task and the instances test when on methylphenidate (Solanto and Wender, 1989), but González-Carpio et al. found children with ADHD off medication to perform better on all subtests of the Torrance Tests of Creative Thinking-Figural (González-Carpio Hernández and Serrano Selva, 2016). Complicating a clear comparison between these two studies is that there are many differences between them, e.g. the assessment instruments (verbal versus figural) and the design of the study (multiple sessions versus two sessions, placebo-controlled versus on and off medication, and double blind design versus no parties being blind to the medication intake).

Testing the effects of psychostimulants in healthy adults using cross-over designs also showed null effects for the main effect of stimulant use on creativity outcomes in all four studies (Baas et al., 2019; Farah et al., 2009; Gvirts et al., 2016; Ilieva et al., 2013). However, two interesting and independent interaction effects were found in two different studies (Farah et al., 2009; Gvirts et al., 2016). The first study showed Adderall (a combination of four salts of amphetamine) to interact with baseline convergent thinking performance (Farah et al., 2009): Adderall enhanced performance on the embedded figures test and the Remote Associations Task in individuals with lower baseline convergent thinking performance, and impaired performance in those with higher baseline convergent thinking performance. The second study showed that the effect of methylphenidate interacted with the personality trait novelty seeking: Methylphenidate increased divergent thinking in individuals with lower novelty seeking scores, while it reduced divergent thinking in individuals with higher novelty seeking scores (Gvirts et al., 2016).

The overall conclusion after reviewing these twelve studies is that there is no strong evidence across these studies that psychostimulants have a negative effect on creative performance in people with an ADHD diagnosis or a higher level of ADHD symptoms. The only result that matches the experience of patients of psychostimulants repressing their creative abilities (Brinkman et al., 2012; Kovshoff et al., 2016) was reported by the study of Gonzales-Carpio and colleagues. How can this be explained? To properly assess the effects of psychostimulants on creativity, a randomized placebo controlled design should be applied to give us any direction on the effects. Of the eight published studies involving subjects with ADHD, six do not meet these criteria (Boot et al., 2017a; Funk et al., 1993; González-Carpio Hernández and Serrano Selva, 2016;

Sam et al., 2020; Swartwood et al., 2003; White and Shah, 2011). This is partly due to the fact that some studies' primary aim was not to assess the effect of medication, but were post-hoc tests in order to assess if their main effects were not influenced by medication (Boot et al., 2017a; White and Shah, 2011). In addition, the effect of withdrawal of using currently prescribed methylphenidate versus never having used methylphenidate might not be comparable situations and could therefore lead to different effects. For example, increased levels of cerebral blood flow in cortical regions have been found after brief discontinuation of methylphenidate treatment (Langleben et al., 2002). Therefore, clustering these together in one group might lead to missing effects (Douglas et al., 1995). For studies on subjects with an ADHD diagnosis, this leaves only the Solanto study with the optimal design. This study shows a positive effect of methylphenidate on divergent thinking. However, we need to be aware that this is an artificial laboratory setting, where subjects have to perform a task that they might not be particularly interested in. We could hypothesize that in situations where patients are engaging in creative behavior of their own choice, medication has different effects.

Interindividual differences should be considered to better understand the effects of psychostimulants on creativity in ADHD. It is not surprising that novelty seeking, a personality trait that is associated with exploratory behavior in novel situations, interacts with the effect of methylphenidate on creative performance because novelty seeking is by itself strongly associated with dopaminergic functioning (Ebstein et al., 1996; Gocłowska et al., 2019). It is likely that the level of novelty seeking is indicative of individual baseline levels of dopamine transmission in the brain. Like other cognitive functions, creativity is expected to have a u-shaped association with dopaminergic functioning and therefore the effect of methylphenidate highly depends on where an individual is on this u-shape at baseline (Cools and D'Esposito, 2011; Linsen et al., 2014).

In conclusion, the effect of methylphenidate on one's creativity is expected to be complex and highly dependent on individual differences in baseline levels of dopamine transmission, indicated by, for example, personality traits or cognitive traits under the influence of dopamine. Future studies with a double blind placebo controlled cross-over design will lead to a better understanding of the effects of psychostimulants on creative performance in the context of ADHD. In addition, explorative research should be directed at identifying additional individual factors that interact with the effects of psychostimulants and we should think of assessment methods that move away from standardized creativity tasks but are more tapping into the self-selected creativity for which there is high intrinsic motivation. This field is in its infancy, but given the high proportion of patients taking stimulant medication, up to 62 % in children (Danielson et al., 2018), and the strong beliefs of patients about its effects on creativity, it deserves our attention.

4. Quality of creativity studies related to ADHD

As described before in Section 3, we have extracted additional information from the selected studies that could be indicators of study quality. Our rating of the quality scores of all studies included in this review can be found in Supplementary Table 2,3,4 and 5, and the summary of those quality scores can be found in Supplementary Table 6. A subset of the quality scores were rated by three raters and the inter-rater reliability analysis showed substantial agreement (average Cohen's kappa of 0.76). The intraclass correlation coefficient for the total quality scores also showed substantial agreement, ICC = 0.77.

The criterium with the highest scores is the 'ADHD assessment' criterium, with average ratings between 0.83 for creative abilities/achievements and 1 for convergent thinking studies (1 is the maximum score). In 75 % of the studies an ADHD diagnosis was determined by a psychiatrist, psychologist or pediatrician or ADHD symptoms in the population were rated using a validated ADHD rating scale. The second best quality parameter was the 'use of an established creativity

instrument'. Most studies used validated instruments that had been used before. Some studies used experimental tests but almost always in combination with validated instruments. The exception comes from the largest population studies, where they used *type of profession* as creativity measure (Kyaga et al., 2013) and self-ratings of creative abilities in relation to their peer group (DuPaul et al., 2017). The criteria that represent additional factors of influence on creativity measures ('age, sex and IQ matching' and 'information about psychiatric comorbidities') deserve our attention because they score around 0.5 or lower. It is important to always have an IQ measurement, as IQ explains a substantial proportion of the variation in creativity scores (Silvia, 2015). Comorbid disorders are also of importance because previous research has already shown strong links between creativity and both schizophrenia and bipolar disorder (Acar et al., 2018; Simeonova et al., 2005; Power et al., 2015). If we want to research the link between ADHD and creativity it is important to know that the subjects do not have other disorders that are strongly linked with increased creativity. The lowest quality scores are for the criterium 'sample size', with a range of average quality scores of 0.05 (divergent thinking studies) to 0.5 (creative abilities/achievements). The average 0.5 rating comes mainly from the two large population-based studies that have suboptimal creativity assessments. Therefore, in order to increase the quality of the studies in the field of ADHD and creativity, most attention needs to be drawn to increasing the sample size of the studies, especially for the studies of divergent and convergent thinking.

5. The neuroscience of ADHD and creativity

Would neuroscientific evidence give us support or direct us towards a better understanding of a link between ADHD and creativity? The following section aims to further our understanding of the potential behavioral link between creativity and ADHD and shed light on the possibilities that are present in neuroscientific research. For this purpose, we below summarize findings from robust genetic and neuroimaging studies for the distinct research fields of both ADHD and creativity, aimed at identifying the overlap between the two. As the overlap in results between the two fields is indirect evidence for a link, we want to be careful and therefore only rely on robust studies, in this case meta or mega-analyses of genetic and neuroimaging studies. A complete review of all individual research reports would not fit the scope of this paper. Our starting points are the robust genetic and neuroimaging studies of ADHD, as we want to understand creativity as a characteristic of ADHD.

5.1. The underlying neuroscience of ADHD and creativity: genetics

Genetic studies in ADHD have identified many genes associated with the disorder (Franke et al., 2011). A meta-analysis of these candidate genes studies in ADHD have identified genes associated with dopaminergic and serotonergic functioning (Gizer et al., 2009): the dopamine transporter gene *SLC6A3/DAT1* and genes coding for the D4 and D5 dopamine receptors, *DRD4* and *DRD5*, the serotonin transporter encoding gene *SLC6A4/5HTT* and a serotonin receptor gene, *HTR1B*. Suggestive association was found for a gene encoding dopamine beta-hydroxylase (*DBH*), adrenoceptor alpha 2A (*ADRA2A*), tryptophan hydroxylase 2 (*TPH2*), and monoamine oxidase A (*MAOA*). Recently, new ADHD genes have been identified in the first genome-wide association study with significant hits. These hits were found for example in the *FOXP2* gene, previously found associated with speech and language disorders (Fisher and Scharff, 2009) and the gene called *SEMA6D*, involved in axon pathfinding (Demontis et al., 2019). There are many other genes associated with ADHD but as effect sizes of single genetic variants are very small, it is of importance for further interpretation to only consider those genes that show a robust association with the phenotype.

The reason why this is so interesting is that there are also associations

of variants in these ADHD genes with measures of creativity. In 2011, Runco and colleagues tested the association between ADHD candidate genes *DAT1* and *DRD4*, among other genes (Runco et al., 2011). In a sample of 147 healthy adult subjects they found the group with the genetic marker that is associated with hypodopaminergic functioning (carriers of the 9 repeat allele of *DAT1* and carriers of the 7 repeat allele of *DRD4*) to have lower scores on verbal fluency and figural and verbal originality. In a re-analysis of these data they focused on gene-by-gene interactions (Murphy et al., 2013). There were no significant *DAT1*-by-*DRD4* interaction effects on creativity measures when correction for multiple testing was applied. The presence of the 7 repeat allele of *DRD4* and the association with divergent thinking was again the subject of investigation in a study of 185 healthy subjects (Maysless et al., 2013). In this study they found the group with the 7 repeat allele exhibiting lower fluency and flexibility scores compared to the group without a 7 repeat allele, but no differences were found in terms of originality. In a sample of 100 healthy adults, divergent thinking and creative achievement scores were compared between groups with and without the 9 repeat allele of the *DAT1* gene. No main effect of *DAT1* group was found for any of the creativity measures. The researchers did find an interaction effect for the *DAT1* gene and the catechol-O-methyltransferase (*COMT*) gene on the selected creativity measures (Zabelina et al., 2016b). This gene provides instructions for making the *COMT* enzyme that breaks down dopamine and has been linked to ADHD (Taylor, 2018). It needs to be noted that the interaction effect for *DAT1*-by-*COMT* again does not hold when adequate methods for multiple testing were applied.

For serotonergic ADHD candidate genes there are two studies that investigated the association with creativity measures. Three *5-HTTLPR* genotype groups were compared on verbal and figural creativity scores (Volf et al., 2009). The short allele of the functional polymorphism in the promoter region of the *5-HTT* gene, *5-HTTLPR*, is often found to be associated with decreased gene expression and decreased rate of serotonin uptake (Lesch et al., 1996). Significant effects for genotype group on verbal and figural creativity were found, with the short allele carriers ($n = 46$) showing higher verbal creativity than the group of subjects with long/long genotypes ($n = 16$). For figural creativity it was the short allele homozygous group ($n = 36$) with the highest scores. In other words, those with genotypes associated with decreased rates of serotonin uptake show the highest creativity scores. The authors conclude that these results do not seem to conflict with the association between the short allele and mental disorders, as creativity has been linked to affective disorders before. They even elaborate about the evolutionary advantage (creativity) of the short allele that counterbalances the disadvantage of the vulnerability to mood disorders. This is an interesting theory in light of ADHD candidate genes as well: the relation between ADHD and the *5-HTTLPR* is ambiguous as in the initial meta-analysis the significant risk allele was the long allele (Gizer et al., 2009), but a more recent meta-analysis could not confirm an association with either the long or short allele of *5-HTTLPR* and ADHD risk (Lee and Song, 2018), which could be due to gene-environment interactions (e.g. Meer et al., 2015). By far the biggest sample of subjects ($n = 543$) was used in a study on the link between the ADHD candidate gene *TPH2* and divergent thinking (Zhang and Zhang, 2017). This gene encodes TPH, which acts as a rate-limiting enzyme in the biosynthesis of 5-HT and therefore belongs to the category of serotonergic genes. The researchers identified a significant association between two *TPH2* Single Nucleotide Polymorphisms (SNPs) (rs11179066 and rs17110747) and verbal fluency and figural fluency and three *TPH2* SNPs (rs6582071, rs4570625, and rs11178999) were associated with figural originality. One of these SNP's received the most attention, because it is in the promoter region of the gene and is involved in gene expression, rs4570625. Previous work had already shown that the T-allele of this SNP was associated with deficits in suppression of task-irrelevant information, poor executive control and increased activity in frontal and parietal parts of the brain during working memory (Reuter et al., 2008,

2007; Strobel et al., 2007). The mechanisms of the other SPNS need to be examined in future studies.

Most of these above-mentioned studies are not meeting the current standards of genetic testing in terms of sample size, correction for multiple testing, and replication. However, the field is progressing rapidly, with many new genes being discovered. For example, there is a first genome wide association study on the scores of the figural form of the Torrance Test of Creative Thinking. This study identified SNPs of various genes, among which were genes with glutamate and GABA functionality (Liu et al., 2018). These are excellent candidates to test further in light of ADHD (Naaijen et al., 2017, 2015). Given all this genetic evidence, the mechanism of potential overlap between genetic factors associated with creativity and ADHD deserves our attention – particularly with respect to the current technological and statistical possibilities of genetic analysis: one can analyze the entire dopaminergic pathway, all genes related to dopaminergic functioning, instead of focusing on one candidate gene only. This will significantly advance our understanding of genetic and neural underpinnings of creativity. The remaining challenge is the need for large samples to generate enough power to detect effects that can survive multiple comparison correction. It is highly recommended to add creativity tasks to existing test batteries.

5.2. The underlying neuroscience of ADHD and creativity: neuroimaging

There is more evidence for overlapping mechanisms coming from neuroimaging studies. Large-scale structural neuroimaging studies have identified structures in striatal and limbic regions as well as cortical surface area to be smaller in individuals with ADHD (Frodl and Sko-kauskas, 2012; Hoogman et al., 2017; Hoogman, M. Hoogman et al., 2019; Nakao et al., 2011). These effects also translate to the population with similar cortical regions affected by ADHD symptoms in the population (Hoogman et al., 2019). A meta-analysis of functional imaging studies across a range of cognitive tasks has shown hypoactivation in individuals with ADHD relative to controls in executive function (frontoparietal network) and attention (ventral attentional network), and hyperactivation in ADHD relative to controls for default, ventral attention, and somatomotor networks (Cortese et al., 2012). The default mode network is also differently activated during rest in individuals with ADHD (Mohan et al., 2016; Rubia, 2018). This network also shows lower connectivity within the network and lower connectivity with the frontostriatal circuits (Faraone et al., 2015; Posner et al., 2014).

Although there are no studies directly assessing the overlapping brain networks in ADHD and creativity, nor functional imaging studies of creativity tasks in ADHD, the meta-analyses of brain regions involved in creative processes show overlapping regions with the ones mentioned above. A meta-analysis of structural neuroimaging studies related to divergent thinking measures (Wu et al., 2015b) included both voxel based morphometry (VBM) and diffusion tensor imaging (DTI) studies. This research indicates an association between divergent thinking and the insula, middle and superior temporal gyrus, cingulate gyrus, caudate tail, cuneus, and middle occipital gyrus. The interpretation of the directionality is difficult and depends on the location. There is an overlap between these structures and structures associated with ADHD in the largest structural brain study in ADHD. Five of these structures were shown to have smaller surface areas in children with ADHD compared with healthy controls (Hoogman et al., 2019).

A meta-analysis of fMRI studies using various creativity tasks identified roles mainly for left hemispheric regions such as the caudal lateral prefrontal cortex (PFC), the medial and lateral rostral PFC, and the inferior parietal and posterior temporal cortices. Separating results based on type of task, showed that tasks involving the combination of remote information (combination tasks) activated more anterior areas of the lateral PFC compared with tasks involving unusual idea generation tasks. The region that was shared between both types of tasks were the caudal prefrontal areas (Gonen-Yaacovi et al., 2013). Meta-analytic

findings only including divergent thinking measures during fMRI tasks indicated the inferior parietal lobule, amygdala, (middle) frontal gyrus, precentral gyrus and middle temporal gyrus as regions with increased activity during divergent thinking tasks (Wu et al., 2015a). Deactivation was found also in the inferior parietal lobule and the precuneus.

Recent work, taking a network perspective on the neuroscience of creativity, highlights a role for the interaction between the default mode network, the executive control network, and the salience system. It was shown that the creative brain is characterized by increased activity among these networks as compared with a less creative brain (Beaty et al., 2018, 2019). A review about brain networks associated with flexibility and persistence, the core processes of creative thinking, highlights the important role played by the striatal and prefrontal network and how it needs a balance within this network rather than excessive activation within either the striatum or the prefrontal cortex (Boot et al., 2017d). This is also a key network involved in ADHD pathology (Cubillo et al., 2012; Faraone et al., 2015; Sanefuji et al., 2017).

All of the above is only indirect evidence of an overlap between brain regions (PFC, striatum, amygdala, etc.) and brain networks (default mode and executive network) involved in ADHD and creativity. As the brain is a complex organ and many other cognitive and behavioral functions have links with these brain regions, the overlap between ADHD and creativity is speculative. However, we indicated here that many regions in the brain are of interest to elucidate the neuroscience underlying ADHD and creativity. What is entirely lacking and has the highest priority is direct links between networks related to ADHD and creativity instead of indirect links. Future research combining ADHD variables and task-based brain activation during divergent thinking should find more direct evidence of the underlying neurobiological systems involved.

6. Conclusions and discussion

With this review we have provided an overview of the current status of research in the field of ADHD and creativity. We summarized the published research across three different aspects of creativity (i.e. divergent and convergent thinking and creative abilities/achievements), in children and adults with ADHD and in those with self-reported ADHD symptoms in population based studies. The research on the link between creativity and ADHD is scarce, but research on divergent thinking shows that, compared with individuals with low rates of self-reported ADHD symptoms, individuals with high rates of self-reported ADHD symptoms perform better on divergent thinking tasks, while those with an official diagnosis of the disorder do not perform well. However, there are still inconsistencies for divergent thinking that need to be studied further. For convergent thinking, results are clearer: There is no evidence of increased convergent thinking abilities in individuals with ADHD or those with a higher number of self-reported ADHD symptoms. An overall positive trend of increased creative achievements among individuals diagnosed with ADHD was shown. Finally, psychostimulants did not show the often heard negative effects on creative thinking, but most research designs were suboptimal for studying these effects. Our quality analysis shows that ADHD assessments and the use of established creativity instruments is sufficient, but the sample size of studies is often too small. We also shed our light on evidence from a neuroscience perspective (neuroimaging and genetics) suggesting candidate systems that should be studied further.

6.1. New insights and avenues for future research

Taking a closer look at the results for divergent thinking, it appears that it is not the diagnosed ADHD patients with increased divergent thinking skills, but rather those with higher self-reported symptom scores without the full disorder. There could be a dose-response relationship as is the case for schizophrenia (Acar et al., 2018). This is an interesting effect that should be studied further, for example by using

the same creativity instrument in clinical studies and population-based studies to cover the entire ADHD distribution. This way it will be possible to map creativity performance across the entire distribution of ADHD symptoms. Support for this effect is also present in data from the Swedish national registries: among individuals with creative professions there is a higher rate of offspring of individuals with ADHD. This offspring is non-affected but do share genetic and environmental factors with those who have ADHD. Thus, the offspring might have the right etiological baggage for increased creativity, but are not hampered by the disorder (Kyaga et al., 2013). In addition, work of Carson and coworkers focused on low latent inhibition (LLI, the inability to screen from conscious awareness stimuli previously experienced as irrelevant), an aspect of distractibility/attention. They showed that LLI is associated with increased creative performance, but only in those with high general mental abilities (Carson et al., 2003). The idea behind this interaction effect is that the remote and seemingly irrelevant knowledge that may be activated as a result of LLI may result in creative ideas, but only when people have the capacity to effectively transform and use this highly diverse and often irrelevant knowledge. An important implication is that general mental abilities can both mask the deficits associated with ADHD and facilitate the use of the more remote and seemingly distracting knowledge that often accompanies ADHD. Therefore, to further investigate this phenomenon, we need to study what cognitive (dys) functions are responsible for masking as well as improving creative performance. A good example candidate is inhibitory control, as this has been shown to be involved in both divergent thinking (Radel et al., 2015) and ADHD (Pievsky and McGrath, 2018) and therefore deserves priority attention.

Other avenues for research come from gaps and limitations of the studies that have been performed so far. One of the biggest limitations is the statistical power in the majority of the studies (with some exceptions). In our review, the case-control studies had sample sizes that ranged between 32 and 110, with most studies having around 40–90 subjects. Expecting effect sizes to be small to moderate (Cohen's d of 0.15–0.3) comparable to other cognitive phenotypes, these samples are underpowered to detect effects. Only by increasing the sample size can we answer our research questions convincingly. In addition, with larger sample sizes it will be possible to characterize subgroups that are expected to exist, as is the case for other cognitive phenotypes in ADHD (Mostert et al., 2015a, 2015b).

Although the majority of the studies used validated and frequently used creativity tests, we also observed that 14 different instruments were used, not all measuring the same construct (Baas and van der Maas, 2015). Standardizing the battery to assess creativity makes it easier to compare research outcomes. We cannot fully comprehend, for example, why one sample has high scores on 'Task A', measuring divergent thinking, whereas a similar sample has low scores on 'Task B', which also measures divergent thinking. To get a clear picture about creativity in ADHD, research groups should ideally use (a) well-powered samples to reduce sampling error, as well as (b) the same creativity tasks, including tasks that measure divergent thinking, convergent thinking and creative abilities/achievements in the same sample. The great variety of tasks used, together with the limited number of studies published, made us decide not to perform a meta-analysis on the results of the creativity studies. It would be hard to interpret the results of such a meta-analysis. Another issue related to this topic of measuring creativity is the concept of the artificial setting in which the creativity testing is usually done. Research has shown that motivational aspects play a role in the performance on creativity tasks (Boot et al., 2017a). Although this is a general problem in cognitive testing, and possibly even more for ADHD (e.g. Luman et al., 2005), it is an important aspect to keep in mind when drawing conclusions about the results of creative performance tasks in such artificial settings.

Finally, our quality analysis showed that studies can be improved when it comes to providing information about psychiatric comorbidity and matching based on age, sex and IQ. Individuals with ADHD have

comorbid disorders more often than not (Faraone et al., 2015), and mapping the comorbid disorders and doing sensitivity analysis on those data will give us a clearer picture of the relationship between ADHD and creativity. The same is true for IQ, although there is a lot of debate about correcting for IQ in ADHD studies, as IQ and ADHD are associated and by correcting for IQ, some of the variance explained by ADHD is therefore taken away (de Zeeuw et al., 2012b). Also, the association between creativity and IQ is important to take into account, as research shows no direct link between IQ and creativity when subjects have a relatively high IQ ($IQ > 120$) (Jauk et al., 2013), but when the IQ scores are lower, IQ does play a role in creative performance. This is another reason why it is important to match for IQ in case-control studies.

Generalization and replication of effects is mostly missing in the current research field. To optimize generalization we should move away from studying college students and try to include adults of all ages from the population by for example trying to add creativity tasks to large, ongoing population studies. In order to provide the field-robust effects, replicating research findings should become the golden standard instead of an exception.

The field of neuroscience and the etiology of creativity can benefit from new and more powerful state-of-the-art methods such as doing genetic pathway analysis (i.e. investigating the entire dopaminergic pathway instead of only looking at one dopaminergic candidate), or using a polygenic risk score (adding all genetic risk scores for a certain trait instead of only looking at one). Also, similar dopaminergic candidates have been linked in separate studies to both creativity and ADHD. What remains unanswered is, if variation in dopaminergic genes provide for direct links between creativity and ADHD. For neuroimaging, alterations in the ADHD brain and brain regions linked to creativity have been identified, but despite overlap in associated regions and mechanisms, no studies have directly linked the ADHD brain and the creative brain. Of particular interest are frontal-striatal brain regions (Cubillo, et al., 2012; Faraone et al., 2015; Heilman, 2016; Hoogman et al., 2017; Takeuchi et al., 2010): individuals with ADHD often have weaker cognitive control (frontal-striatal), leading e.g., to problems with inhibiting a response; increased bottom-up (striatal-frontal) activity is also often observed in ADHD, leading to increased flexibility and impulsivity (Hoogman et al., 2011, 2013). Divergent thinking is linked to similar brain phenotypes (Boot et al., 2017d; Heilman, 2016). An integrative study of the above will improve our understanding of the underlying networks associated with both concepts. Another gap in the field of neuroscience is the lack of multimodal analysis of imaging measures in creativity research.

6.2. Concluding remarks

ADHD is well-known for its deficits, but there might also be advantages associated with ADHD. Researching creativity in ADHD is a promising field, given the previous research that shows potential links. A focused research agenda will improve our understanding of the link between creativity and ADHD, generating a more complete picture of the issue at hand. The increase of knowledge about the positive aspects of ADHD may aid in treatment and coping with ADHD, reduce stigmatization, and increase the quality of life of patients. When fundamental research can be translated to more practical implications such as educational programs in the classroom, it has the potential to relieve the biggest societal burden of ADHD, namely educational costs (Le et al., 2014).

Declaration of Competing Interest

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.neubiorev.2020.09.029>.

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