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Review

Neuroimaging creativity: A psychometric view

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ABSTRACT

Many studies of creative cognition with a neuroimaging component now exist; what do they say about where and how creativity arises in the brain? We reviewed 45 brain-imaging studies of creative cognition. We found little clear evidence of overlap in their results. Nearly as many different tests were used as there were studies; this test diversity makes it impossible to interpret the different findings across studies with any confidence. Our conclusion is that creativity research would benefit from psychometrically informed revision, and the addition of neuroimaging methods designed to provide greater spatial localization of function. Without such revision in the behavioral measures and study designs, it is hard to see the benefit of imaging. We set out eight suggestions in a manifesto for taking creativity research forward.

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1. Introduction

What counts as creativity? How do you measure it? Can we decipher its neural signature in the brain? These are the central questions in the neuroscience of creativity. In this report we review empirical publications on creative cognition that have an imaging component; then we suggest future directions for the field.

How do you test for creativity? In the oldest scientific journal, an eyewitness described his encounter with the young Wolfgang Amadeus Mozart thus: "I said to the boy, that I should be glad to hear an extemporary *Love Song,* ... He then played a symphony which might correspond with an air composed to the single word *Affetto* [('con Affetto' means 'with love')]. It had a first and second part, which together with the symphonies, was of the length that opera songs generally last ..." [1]. The writer, who was greatly impressed by the young Mozart, reported to the Royal Society that, charmingly, between *de novo* compositions, the young boy would not desist from playing with his cat, nor from running around with a stick between his legs. Even prodigies like to play horse. Mozart's musical mastery was characterized by accuracy and fluency in intellectually challenging sight-reading, but his capacity to innovate, evaluated by his older contemporary, Daines Barrington, defines him as a creative genius.

It is much easier to identify creative people or work in hindsight than to capture exactly what we mean by creativity in a semantic net. Are luminous creative geniuses like Mozart at the far end of a normal distribution? Or is creativity qualitatively heterogeneous? Is the 'juice' of creativity that ran in Leonardo da Vinci's veins the same juice that fuelled Marie Curie? These are the same kinds of questions that have been asked about many phenomena in the history of science; even those that are apparently lower order and more simple. Our primeval ancestors could manipulate heat, but Brownian motion (which describes heat kinetically) was not discovered until 1827 (and then not by a physicist but by a botanist). It is not surprising that it is taking decades to characterize and measure creativity. Given the heterogeneity of creative expression, and the relative youth of the field, it is perhaps to be expected that there is little consistency in the findings that we reviewed for this article.

Creativity in humans is a complex behavior involving utility, beauty, and innovation (see for working definitions [2,3]. The want of an exact specification is not an important impediment. 'Species' and 'genes' are the bread and butter of biologists and geneticists yet there is a precise definition of neither; refinements to complex constructs often emerge over time. How is creative cognition measured currently?

Researchers generally use two broad classes of creative cognition tasks: 'divergent' and 'convergent'. Divergent thinking tests are instruments that have been designed to be open-ended (to afford multiple correct answers, such as 'describe what would happen if rain was green') [4]. Convergent tests or items are those that have a single correct answer (such as 'which solar planet is closest to Earth in density?') A serious challenge to operationalising creative cognition is that tests with a convergent answer tend to measure intelligence, whereas tests with an open (subjective or rater-scored) answer tend to have lower reliability and validity. There is evidence that peer ratings on some creative cognition tasks show reasonably high inter-rater agreement which increases the usefulness of the tests [5].

In the work we have read, no creativity researcher claims that either a single scale or test battery circumscribes the construct adequately. As has been said forcefully [6], the manifestations and causes of creative cognition are plural. There is insufficient evidence yet to say whether or not creative cognition is psychometrically unitary as is the case with the *g* factor in intelligence [7]. Currently used creative cognition measures depend on intuitions about processes (such as fluency of answer production, finding correct solutions in a problem-space, or finding open solutions in a problem-space) that seem suitable candidates for exploration. Since Joy Paul Guilford gave his Presidential Address to the American Psychological Association in 1950 [4], there has been a keen appreciation of the need for psychometric measurement of creative cognition.

Here we summarize recent empirical reports of creative cognition that include a neuroimaging element. We identified published reports by searching abstracts in Web of Science and other databases that included the words creativity, divergent thinking and (using Boolean operators) fMRI, MRI, imaging, EEG, PET, MEG, SPECT, rCBF, ASL, DTI and NIRS. We did not include studies from contiguous and relevant areas such as 'insight' or 'innovation' unless they also included creativity explicitly because we aimed to focus narrowly on the central construct. We culled only non-empirical studies and those empirical studies carried out in patient populations. This approach carries with it the distinct advantages of simplicity, limitations upon the need for human choice in what is "in" or "out" of consideration, reproducibility, and thus generalizability to future inquiries.

2. Neuroimaging

Brain-imaging research affords various ways of seeing behavior instantiated in electrical signals, blood oxygen levels, brain structure, cerebral blood flow or in metabolite concentrations. Creativity researchers deploy a family of imaging modalities. These include diffusion tensor imaging (DTI), electroencephalography (EEG), functional magnetic resonance imaging (fMRI), magnetic resonance spectroscopy (MRS), near infrared optical imaging, positron emission tomography (PET), regional cerebral blood flow (rCBF) and structural magnetic resonance imaging (sMRI). These different ways of seeing fall into two groups: those that investigate function (how does the brain look when it is working on a task?), and those that explore structure (does the task have neuroanatomical correlates?).

3. Functional imaging

3.1. EEG studies

EEG experiments use of a set of electrodes placed on the scalp in a pattern according to standardized templates such as the international 10-20 system (see for description [8], p. 27–30). The outcome of an EEG recording is given as the voltage difference between electrode sites plotted over time (for an excellent exposition on EEG see

[8]). EEG provides excellent temporal resolution regarding when neuronal populations are firing or when interactions between neuronal populations are occurring, but very low spatial resolution of where in the brain these neuronal processes are occurring. The signal received by the electrode must travel through brain matter of varying density, through skulls of varying density, and through skin. Each of these presents an interpretive challenge to defining the spatial source of the signal. In addition individual differences in brain structure and volumes creates 'noise' around the interpretation of the signal.

There exist four features from the EEG trace that are relevant to the current discussion: phase, power, synchronization, and coherence. Phase simply represents the oscillatory activity (positive and negative) from the EEG trace in the responses to experimental events. Researchers can convert the EEG signal to power by squaring the value of each observation on each single trial prior to time-locked averaging. Converting to power allows responses to experimental events that are dissimilar in phase across trials to be characterized. Synchronization represents an increase in the power of ongoing oscillations relative to baseline, while desynchronization indicates a reduction in oscillatory power compared to baseline [9]. Measures which quantify the stability of signal phase across trials are often known as coherence [10,11].

The vast majority of EEG studies report either amplitude (i.e., power) or synchronization changes associated with creative task performance in the alpha band (the range 8–12 Hz). This band has been associated with cognition and memory, and task performance has been associated with alpha power suppression [12]. Thus, alpha increases have commonly been associated with idling or inhibition of cortical regions (such as during eyes closed – although see Klimesch et al. [119], for an alternate viewpoint), while alpha decreases are associated with cortical activity associated with cognition (i.e., during eyes open) [13]. The relationship both within and across various bands (including alpha, beta, gamma, delta) between synchronization, coherence, amplitude and phase (as well as sine and cosine effects) between regions of brain during cognitive activity is beyond the scope of this review. Various authors describe increased alpha, decreased alpha, increased synchronization, increased alpha power; this makes it nearly impossible to discover common findings across studies. Moreover, there is growing understanding that the "evoked response" elicited across trials in an EEG experiment is only a partial response to experimental events [14,15], as the brain is "updating" neuronal assemblies to facilitate task performance over time. The studies we review describe both absolute changes in the alpha band as well as functional couplings between brain regions associated with creative task performance.

We found 28 studies published between 1975 and 2009, comprising ∼1150 subjects (Table 1). Relatively few groups of researchers are represented in our review; the two most prolific are Razumnikova [16–20] and Fink [21–26]. Nearly all EEG studies used measures of divergent thinking, although most of these were homegrown measures as opposed to standardized measures such as the Alternate Uses Test in which participants are asked to list various ways in which a common object (such as a brick) can be used. Scoring is computed from fluency (number of uses), and rarity of response (Alternate Uses Test), or measures from the Torrance battery. Researchers were creative in designing tasks: participants have been asked to: (1) complete Russian proverbs [27], (2) mentally compose a drawing [28], (3) imagine a dance improvisation [23], and (4) formulate hypotheses regarding the development of quail eggs [29]. While the reports are fascinating, it is hard to compare these studies to one another as one might for studies in, say, working memory using the "n-back" paradigm, or attention using the Stroop paradigm [30]. Four studies used the Remote Associates Test [31]. This test is 'convergent' (there is only one correct answer): participants are asked to find the word that can be attached to each of three other words to make three new compound words (for example 'salt' can be added to 'lick', 'sprinkle' and 'mine' to form three new words) [18,32–34], although one group used an alternative measure of creative insight [25]. Four studies used the Alternate Uses Test or similar items, although three of these were from one group [21,22,25,34].

One place to look for convergence among EEG studies is in the three Remote Associates Test studies conducted by three independent groups. In one study researchers found that subjects performing well on the test had no significant decrease in alpha associated with performance across an intelligence test and Alternate Uses Test, although they did exhibit high alpha reactivity across trials. The authors interpret this reactivity as reflecting task effects as opposed to focusing or defocusing attention [34]. Localization in this study is limited due to electrodes being placed only in the occipito-parietal region (O_2-P_4). A second study that used the Remote Associates Test (N = 30) found lower alpha power in bilateral parietal (left P3, Pz, right P4), and left frontal region (F4) compared with a word categorization task [32]. Lower alpha coherence between several frontal and temporal regions was seen in a third Remote Associates Test study (N = 39) [18]. This experiment included 16 scalp electrodes; the creative cognition task was compared with performance on the Scholastic Aptitude Test (SAT). Alpha power was significantly lower and desynchronization was increased during performance of the Remote Associates Test as compared to the SAT, particularly in posterior brain regions [18]. Finally, Jung-Beeman [33] conducted fMRI and EEG experiments in separate groups of subjects undergoing the Remote Associates Test. Their findings were more precise: they hypothesized and found a discrete gamma burst (transient increase and subsequent decrease of gamma power) in the right anterior temporal lobe associated with self-reports of solving insight problems (but not self-reported non-insight solutions). An alpha burst was also found to be associated with insight under a right posterior parietal electrode [33]. Interestingly, the alpha burst appeared to precede the gamma burst by nearly one second (Jung-Beeman – Figure 6). In summary, the performance of the Remote Associates Test is associated with alpha power changes in right posterior brain regions across three independent studies. These authors have variously interpreted these changes to reflect low cortical activation [34], defocused attention [18], and early unconscious solution-related processing [33].

Several studies have used variants of the Alternate Uses Test (AUT). In the earliest study we reviewed [34], researchers found that people with the highest ideational fluency on the AUT, showed higher alpha levels (although reduced from baseline) while performing all behavioral tasks (85.4% of basal alpha compared to 37.1% for low performers). Fink et al. [26] studied 30 subjects either trained to perform divergent thinking tasks or not, and found that the trained group displayed higher task-related synchronization of frontal alpha activity. This is interpreted as a selective top-down inhibition process that prevents information processing from being disturbed by new external stimuli [21]. In a subsequent study, these same researchers found that more extraverted subjects who performed best on measures of divergent thinking (including the AUT) showed the highest level of alpha synchronization; more introverted subjects who performed poorly showed the lowest alpha synchronization [25]. Finally, in a study of 47 subjects, these researchers found that thinking of unusual uses for common objects was accompanied by a stronger synchronization of EEG alpha activity (both in the lower and in the upper alpha band), particularly in frontal regions of the brain [22].

There is considerable heterogeneity of findings across EEG studies of creative cognition, making it difficult to draw strong conclusions about the impact (or sometimes even direction) of alpha activity, synchronization and localization of these factors within

Table 1
EEG studies of creative cognition.

Author/date	*N*	Phenotype	Key results from abstract
Martindale and Hines (1975) [34]	32	Remote Associates Test (RAT), Alternate Uses Test (AUT), IPAT Cattell Culture Fair test (CCFT).	High scorers on the AUT operated at a high percentage of basal α during all tests while high scorers on the RAT showed differential amounts of α presence across tests, with the highest percentage of basal α during tests of creativity and the lowest percentage during the intelligence test.
Martindale et al. (1984) [103]	Ex1: 24	Ex1: 3 speech tasks (random, discursive, and fantasy speech).	Ex1: High AUT scores exhibited higher α activity than low AUT. Higher right hemisphere for α. Significant interaction: high RAT with high AUT ("most creative") indicated higher left hemisphere α band power; low RAT with low AUT also indicated higher left hemisphere α band power.
	Ex2: 38	Ex2: write 2 fantasy stories in response to cards from the Thematic Apperception Test.	Ex2: high–high group showed higher left hemisphere α (experiment 1 replicated).
	Ex3: 21	Ex3: artists versus non-artists non-creative verbal task (reading economics article) or creative drawing class (drawing a cow's vertebra).	Ex3: For all subjects, right hemisphere α was greater than left during reading; for creative subjects, left hemisphere α amplitudes were greater than right. Thus, creative subjects showed higher task-specific asymmetry than non-creative subjects.
Petsche (1996) [104]	38	Verbal task: (make a story with 10 words), look at 4 pictures, memorize them, create a new mental picture. Musical: compose a piece of music mentally, then note it down after the EEG.	Acts of creative thinking, be it verbally, visually or musically, are characterized by more coherence increases between occipital and frontopolar electrode sites than any other mental tasks.
Jaušovec (1997) [105]	Ex1: 26 Ex2: 25	Ex1: comparing ill-defined (number problem) to well-defined problems (missionaries and cannibals problem). Ex2: Comparing pre-solution stages (reading, planning), and solution stages (solving, information selecting, analogous solution).	Students displayed lower α power while reading the ill-defined problem and planning its solution than during the preparation phase of the well-defined problem. A reverse pattern of α power was obtained for processes that were directly involved in the solution of both problem types.
Mölle et al. (1999) [106]	28	Four divergent thinking tasks. Visual and verbal. What are consequences of being able to fly. AUT. Think of funny similarities between two pictured objects (cat and mouse). Complete a line picture.	The dimensional complexity of the EEG was greater during divergent thinking than during convergent thinking. While solving tasks of divergent thinking, subjects with high performance scores had a lower EEG dimension than did subjects with low scores, in particular over frontal cortical areas.
Krug et al. (1999) [78]	16	Stories from Guilford's test repertoire – divergent thinking.	EEG complexity was higher during divergent than convergent thought, but this difference remained unaffected by the menstrual phase. Influences of the menstrual phase on EEG activity were most obvious during mental relaxation. In this condition, women during the ovulatory phase displayed highest EEG dimensionality as compared with the other cycle phases, with this effect being most prominent over the central and parietal cortex. Concurrently, power within the α frequency band as well as θ power at frontal and parietal leads were lower during the luteal than ovulatory phase.
Jaušovec (2000) [107]	49	A bespoke 'dialectic open problem' and 6 divergent production problems. Subjects were asked to think about solutions not write them down.	The analysis of EEG measures in Experiment 1 indicated that highly intelligent individuals showed higher α power (less mental activity) and more cooperation between brain areas when solving closed problems than did average intelligent individuals. In Experiment 2, highly creative individuals displayed less mental activity than did average creative individuals when engaged in the solution of different creative problems. Creative individuals also showed more cooperation between brain areas than did gifted ones, who showed greater decoupling of brain areas when solving ill-defined problems.
Jaušovec and Jaušovec (2000) [108]	30	Six divergent problems adapted from Wallach and Kagan '65. 3 were verbal (uses of a tyre), 3 figural – mentally complete the unfinished picture. Dialectical problem was to write about a war given fictional information prompts.	Differences in EEG power measures were mainly related to the form of problem presentation (figural/verbal). In contrast, coherence was related to the level of creativity needed to solve a problem. Noticeable increased intra- and interhemispheric cooperation between mainly the far distant brain regions was observed in the EEG activity of respondents while solving the dialectic problems.
Razoumnikova (2000) [16]	36	Convergent task was mental arithmetic (addition). Poisonous snakes problem as index of divergent thinking.	When compared with the rest (condition), both mental experiences (convergent and divergent) produced the significant desynchronization of α1,2 rhythms.

Table 1 (*Continued*)

Author/date	N	Phenotype	Key results from abstract
Danko et al. (2003) [32]	15	Mednick's Remote Associates Task – linking string of 12 words from different semantic fields with associated words (nouns) (D state); test of general psychological knowledge (E state).	Noteworthy are the lower power of the α1 and α2 oscillations in the left and central parietal areas and the lower power of the α2 oscillations in the right parietal and left frontal areas in the D state in contrast to the E state.
Razumnikova (2004) [17]	63	"Divergent Thinking" with eyes closed.	Creative men were characterized by massive increases of amplitude and interhemispheric coherence in the β2 whereas creative women showed more local increases of the β2 power and coherence. On the contrary, the task-induced desynchronization of the α1 rhythm in creative women was topographically more expanded as compared with men who demonstrated greater interhemispheric coherence than women did.
Jung-Beeman et al. (2004) [33]	19	Insight problems from the Remote Associates Test (RAT)	A sudden burst of high-frequency (γ-band) neural activity in the same area (right anterior superior temporal gyrus) beginning 0.3 s prior to insight solutions.
Bhattacharya and Petsche (2005) [109]	19	Mentally compose a drawing of own choice while looking at a white wall. After EEG, sketch it.	Comparing the tasks to rest, the artists showed significantly stronger short- and long-range delta band synchronization, whereas the non-artists showed enhancement in short-range β and γ band synchronization primarily in frontal regions; comparing the two groups during the tasks, the artists showed significantly stronger delta band synchronization and α band desynchronization than did the non-artists. Strong right hemispheric dominance in terms of synchronization was found in the artists.
Jin et al. (2006) [29]	50	Develop a hypothesis about variation in quail eggs.	In contrast to normal children, gifted children showed increased A-CMI (averaged-cross mutual information EEG) values between the left temporal and central, between the left temporal and parietal, and between the left central and parietal locations while generating a hypothesis.
Fink and Neubauer (2006) [24]	31	Verbal IQ test used to split sample on median Intelligence Quotient. 5 verbal creativity tasks administered. Insight Problems, utopian situations, alternative uses, inventing names for random abbreviations.	Creative problem solving was generally accompanied by lower levels of cortical arousal (i.e., increases in α power from a pre-stimulus reference to an activation interval). Additionally, more original (versus less original) responses were associated with a stronger task-related α synchronization in posterior (particularly centroparietal) cortices.
Fink et al. (2006) [21]	30	Divergent thinking, insight task (2 unusual situations that Subjects must provide explanations for), also utopian situations in which Subjects must produce unusual or original solutions. Alternative uses tasks and Word Ending task in which Subjects must complete many solutions to a presented suffix.	The training group displayed higher task-related synchronization of frontal α activity (i.e., increases in α power from the pre-stimulus reference to the activation interval) than the control group.
Grabner et al. (2007) [26]	26	Torrance Test (2 verbal creativity problems).	Analyses revealed that more, as compared with less, original ideas elicited a stronger event-related synchronization of α activity (power increases from the pre-stimulus reference to the activation interval) and higher phase coupling in the right hemisphere.
Nagornova (2007) [110]	30	Four drawing tasks: 2 designated as creative, 2 designated as 'control'.	Statistical analysis of the EEG spectral power for the frequency bands α1, α2, β1, β2, and γ showed that the creative task performance was characterized by an increase in the EEG power in the β2 and γ bands and single differently directed power changes in the α1 and α 2 and β 1 bands.
Razumnikova (2007) [18]	39	Remote Associates Task (Mednick). Simple Associates Task.	Originality scores of the verbal associates positively correlated with an increase of coherence focused in the fronto-parietal regions of both hemispheres in the β2 and in the left parieto-temporal loci in the α1. Additionally, more original responses positively correlated with amplitude of the α1 mostly in the left hemisphere.
Shemyakina et al. (2007) [92]	117	Complete a proverb.	Performance of the creative task was accompanied by a highly significant and reproducible increase in the power of the γ and β2 EEG frequency bands, as well as a less pronounced decrease in the power of the θ band in the central and parieto-occipital cortical areas. In addition, the performance of the creative task was also characterized by an increase in the EEG coherence in the α2, β2, and γ bands.

Table 1 (*Continued*)

Author/date	*N*	Phenotype	Key results from abstract
Razumnikova (2007) [19]	39	Three verbal tasks: fluency, chains of association and Remote Associate's Task.	In creative persons of both sexes, more original associations were accompanied by a decreased α2-rhythm coherence. In non-creative women, interhemispheric interaction was, conversely, increased.
Bazanova and Aftanas (2008) [111]	98	Non-verbal creativity, Torrance non-verbal test as modified by Gilford. Coefficient of creativity plus Fluency, flexibility and originality verbal sub-factors.	Individuals with high α-rhythm maximum peak frequency values and prolonged α spindles were generally characterized by more "fluent" non-verbal intellect. In turn, high levels of originality and intellectual plasticity showed a significant association with a wider range of α activity and variability of α spindle amplitude. The highest levels of originality in solving non-verbal tasks were seen in subjects with the lowest values for individual α-activity peak frequencies.
Fink and Neubauer (2008) [25]	34	Insight task, utopian situations, alternative uses, word ends.	Those extraverted individuals who produced highly original ideas during task performance exhibited the largest amount of α power, while in introverted individuals who produced less original ideas the lowest level of α power was observed.
Sheth et al. (2009) [112]	18	Sixteen verbal brain teasers.	A consistent reduction in β power (15–25 Hz) was found over the parieto-occipital and centro-temporal electrode regions on all four conditions – (a) correct (versus incorrect) solutions, (b) solutions without (versus with) external hint, (c) successful (versus unsuccessful) utilization of the external hint, and d) self-reported high (versus low) insight. γ band (30–70 Hz) power was increased in right fronto-central and frontal electrode regions for conditions (a) and (c). The effects occurred several (up to 8) seconds before the behavioral response.
Danko et al. (2009) [113]	27	Finish the incomplete Russian Proverb with own variant; finish the proverb with the standard variant.	The creative task performance was associated with a marked increase in the EEG power (β2 and γ); significantly more complicated non-creative tasks were not accompanied by marked changes in the EEG power in these bands.
Fink et al. (2009) [23]	32	Dance improvisation task (imagine yourself performing a free-form dance), waltz task (imagine dancing the waltz), Alternative uses of an object task.	We observed evidence that during the generation of alternative uses professional dancers show stronger α synchronization in posterior parietal brain regions than novice dancers. During improvisation dance, professional dancers exhibited more right-hemispheric α synchronization than the group of novices did, while during imagining dancing the waltz no significant group differences emerged.
Fink et al. (2009) [22]	47	Alternative Uses, object characteristics (shoe – leather), Name invention (Subjects given two letters – must think of a noun to match them), word endings.	The generation of original ideas was associated with α synchronization in frontal brain regions and with a diffuse and widespread pattern of α synchronization over parietal cortical regions. The fMRI study revealed that task performance was associated with strong activation in frontal regions of the left hemisphere. In addition, we found task-specific effects in parieto-temporal brain areas.
Razumnikova et al. (2009) [20]	53	Divergent thinking figural and verbal.	There was greater activity in the right hemisphere independent of sex, task or instructions given. A high reactivity of the α_2 rhythm was more marked during verbal creative thinking in women; and that of the β_2 rhythm, during figural creative thinking in men. The instruction-related improvement of the critical selection of solutions was to a greater extent reflected by changes in the cortical activity, more pronounced in the frontal cortex in the women.

α = Alpha; β = Beta; γ = Gamma; θ = Theta.

frontal, posterior, or lateralized hemispheric cortices as is often claimed. Yet creative cognition appears to elicit stronger alpha synchronization across several studies [35]. Creative cognition and alpha synchronization may be mediated by giftedness [29,36] personality [25], and sex [17]. However, it should be noted that there is nothing specific about alpha power synchronization with regard to creative cognition, as this band and its synchronization has been well associated with such diverse cognitive tasks as: high episodic short term memory demands [37], visuospatial working memory [38], and suppression of unattended positions during visual spatial orienting [39].

3.2. fMRI studies

Functional magnetic resonance imaging studies allow researchers to investigate changes in brain activity that occur while participants do tasks while inside an MRI scanner. fMRI exploits the increase in blood flow to the local cerebral vasculature that accompanies neural activity. Increased blood flow results in a corresponding reduction of the local paramagnetic deoxygenated hemoglobin. This is the basis for the blood oxygen level-dependant (BOLD) signal which is detected by the MRI scanner [40]. Statistical procedures are then applied to model spatial and temporal maps to

Table 2
fMRI, PET, SPECT, NIRS and structural imaging studies of creative cognition.

Author/Date	*N*	Modality	Phenotype	Key results from abstract
Goel and Vartanian (2005) [44]	13	fMRI	Match problems [67], divergent thinking.	A comparison of Match Problems versus baseline trials revealed activation in right ventral lateral prefrontal cortex (Brodmann Area 47) and left dorsal lateral prefrontal cortex (Brodmann Area 46).
Howard-Jones et al. (2005) [45]	8	fMRI	Story generation task.	Results support the notion that areas of the right prefrontal cortex are critical to the types of divergent semantic processing involved with creativity in this context (i.e., involved in increased creative effort).
Mashal et al. (2007) [47]	15	fMRI	Processing novel metaphors.	A direct comparison of the novel metaphors versus the conventional metaphors revealed significantly stronger activity in right posterior superior temporal sulcus, right inferior frontal gyrus, and left middle frontal gyrus.
Asari et al. (2008) [43]	46	fMRI	Rorschach – ambiguous figures. Ss scores were determined by the rarity or frequency of their response to the 'blot'.	An event-related analysis contrasting unique versus frequent responses revealed the greatest activation in the right temporal pole, which survived a whole brain multiple comparison.
Kowatari et al. (2009) [46]	40	fMRI	Imagine a new design for a Pen while inside the scanner. After the scan Ss were asked to draw their pen design which was the measurement of creativity.	In the experts, creativity was quantitatively correlated with the degree of dominance of the right prefrontal cortex over that of the left, but not with that of the right or left prefrontal cortex alone. In contrast, in novice subjects, only a negative correlation with creativity was observed in the bilateral inferior parietal cortex.
Starchenko et al. (2003) [50]	9	PET	Creative (given a list of words, form a chain of associations to connect them) and two control tasks: name 5 X object within the category of X (such as tree). Read aloud a sequence of words.	The first pattern of activation immediately referred to the creative process. It embraced the left supramarginal (Brodmann Area 40) and cingulate (Brodmann Area 32) gyri.
Bechtereva et al. (2004) [49]	16	PET	Create a story task using words presented on a screen (hard or easy).	Valuable brain correlates of creativity were revealed in the left parieto-temporal regions (Brodmann areas 39 and 40).
Chavez et al. (2004) [52]	100	SPECT	TTCT: figural and verbal forms.	A positive significant correlation was found between the figural and verbal creativity indexes and the cerebral blood flow in the right precentral gyrus, Brodmann Area 6 ($p < .001$). The figural creativity index also showed correlation with the cerebral blood flow in the right anterior cerebellum ($p < .003$). The creativity index obtained with the TTCT verbal correlated with the right postcentral gyrus, Brodmann Area 3 ($p < .0001$); the left middle frontal gyrus, Brodmann Area 11 ($p < .002$); the right rectal gyrus, Brodmann Area 11 ($p < .002$); the right inferior parietal lobule, Brodmann Area 40 ($p < .003$); and the right parahippocampal gyrus, Brodmann Area 35 ($p < .006$).
Chávez-Eakle et al. (2007) [53]	100	SPECT	TTCT 2 verbal subtests, just suppose and unusual uses.	Subjects with a high creative performance showed greater CBF activity in right precentral gyrus, right culmen, left and right middle frontal gyrus, right frontal rectal gyrus, left frontal orbital gyrus, and left inferior gyrus (Brodmann Area 6, 10, 11, 47, 20), and cerebellum; confirming bilateral cerebral contribution.
Carlsson et al. (2000) [51]	24	rCBF	Creative Functioning Test. Controlled Oral Word Association Test (FAS) and Unusual used of Objects Test.	Calculations were made of differences in blood flow levels between the FAS and the Brick measurements in the anterior prefrontal, frontotemporal and superior frontal regions. In accordance with our prediction, repeated measure-ANOVAs showed that the creativity groups differed significantly in all three regions. The highly creative group had increases, or unchanged activity, while the low creative group had mainly decreases.
Folley and Park (2005) [114]	51	NIRS	Mednick's RAT and study-specific divergent thinking task in which Ss were presented with objects for which they had to state uses. Some objects were familiar, some were novel.	NIRS data showed that DT was associated with bilateral prefrontal cortex (PFC) activation, but the right PFC particularly contributed to the enhanced creative thinking in psychometric schizotypes compared with the other two groups.
Gibson et al. (2009) [115]	40	NIRS	RAT, novel creativity test (Folley's).	NIRS showed greater bilateral frontal activity in musicians during divergent thinking compared with nonmusicians.
Kaasinen et al. (2005) [116]	42	MRI	Personality: Temperament and Character Inventory 240 items of self-report.	A positive relationship was seen between GM (Gray Matter) volume at the border of the temporal, parietal, and frontal cortices, and self-transcendence, a character personality trait that reflects mature creativity and spiritualism.
Jung et al. (2010) [102]	61	MRI	Three divergent thinking tasks: drawing fluency, drawing with pre-specified lines, AUT. Also a questionnaire of already achieved creativity.	A region within the lingual gyrus was negatively correlated with CCI (Composite Creativity Index); the right posterior cingulate correlated positively with the CCI. For the CAQ (Creative Achievement Questionnaire), lower left lateral orbitofrontal volume correlated with higher creative achievement; higher cortical thickness was related to higher scores on the CAQ in the right angular gyrus.

Table 2 (*Continued*)

Author/Date	N	Modality	Phenotype	Key results from abstract
Moore et al. (2009) [117]	21	MRI	TTCT figural subtest.	Torrance Test of Creative Thinking scores correlated negatively with the size of the Corpus Callosum and were not correlated with right or, incidentally, left White Matter Volume.
Jung et al. (2009) [64]	56	MRS	Composite creativity index derived from (1) design fluency test in two conditions, free and four-line [118], (2) AUT [118].	Different patterns of correlations between N-acetyl-aspartate and Composite Creativity Index were found in higher verbal ability versus lower verbal ability participants (i.e., within the anterior cingulate gyrus), providing neurobiological support for a critical "threshold" regarding the relationship between intelligence and creativity.
Jung et al. (2010) [101]	72	DTI	Four Divergent thinking tasks [71]. Verbal and drawing creativity tasks [118], AUT [118], caption generation for New Yorker cartoons.	We found that the CCI was significantly inversely related to FA within the left inferior frontal white matter (t = 5.36, p = .01), and Openness was inversely related to FA within the right inferior frontal white matter (t = 4.61, p = .04).

fMRI: functional magnetic resonance imaging; PET: positron emission tomography; SPECT: single-photon emission computed tomography; rCBF: regional cerebral blood flow; NIRS: near infrared spectroscopy; sMRI: structural magnetic resonance imaging; MRS: magnetic resonance spectroscopy; and DTI: diffusion tensor imaging.

neural activity on a particular task [41,42]. Whereas EEG has high temporal resolution, fMRI has higher spatial resolution, usually at the level of a few millimeters. We do not know whether we should expect blood flow to increase or decrease, within any particular brain region, in more creative people during task performance.

In the seven studies we reviewed [22,33,43–47], no two fMRI studies used the same index to assess creative cognition (Table 2). Examples of the creative cognition tasks include vocalizing a response to a Rorshach blot [43] and imagining a new design for a pen [46]. Is there any overlap across different 'creative' tasks in the region of brain activity reported by researchers? Most of the significant findings in the fMRI studies appeared to be in brain regions unique to each study. Fig. 1 shows axial slices of the brain with regions of interest activated by each task shown schematically. The lack of agreement in brain regions associated with 'creativity' across different tasks is striking. However, this result is not surprising given the exquisite sensitivity of functional imaging paradigms to even slight differences in experimental design parameters (for example see localization results obtained for the classic "stroop" paradigm in [30].

We found topographical regions described variously in terms of Brodmann areas, general regions such as 'prefrontal cortex' as well as more tightly specified names such as left anterior cingulate gyrus [45]. There was some overlap in regions of increased activation in the right medial frontal gyrus [45,46], dorsal lateral prefrontal cortex (BA 9) [44,46], right superior temporal gyrus [33,47], left anterior cingulate [22,45,46], and the left inferior frontal cortex [45,47]. These regions are heteromodal cognitive regions of the frontal, temporal, and limbic lobes (again see [30]), and (1) given the diversity of creativity measures, (2) the broad dependence of these measures upon basic cognitive processes (e.g., attention, working memory, semantic retrieval, etc.), and (3) the lack of controls for individual difference variables relevant to both creative cognition [17,29,25,36] and fMRI BOLD activation, these few results are, at present, uninterpretable.

3.3. PET and SPECT studies

Another group of imaging studies uses PET and single-photon emission computed tomography (SPECT). Positron emission tomography is a technique used to investigate metabolic processes in the brain, based on the radioactive decay of an isotope (called a tracer). The tracer is injected to the bloodstream where it eventually reaches the brain. When the tracer undergoes beta decay, it emits a positron that is then detected by the PET scanner. The most common PET tracer measures the amount of regional glucose uptake [48]. PET can also measure rCBF.

We found two empirical studies that used PET to measure regional cerebral blood flow while participants were doing creative cognition tasks [49,50]. The sample sizes were small (9, 16, respectively) and the creative cognition tasks differed. A third study used changes in regional cerebral blood flow as the outcome variable following a creative cognition task [51]; this last report investigated 24 subjects, characterized as either more or less creative, while they performed a task similar to a Rorschach ink blot test. Each study reports different results. There was some evidence that more creative people showed greater activation in bilateral prefrontal regions when doing the creative cognition task. Less creative people showed increases in the left prefrontal region. Highly creative people showed increases or unchanged activity in the anterior prefrontal, fronto-temporal and superior frontal regions. Less creative people showed decreased activity in those regions [51]. When tasks were compared among the whole sample, there was a significant contrast in activation (corrected at the voxel level for multiple comparisons) in the left supramarginal (BA 40), and cingulate (BA 32 gyri) [50].

Two experiments with some similar characteristics [52,53] used single-photon emission computerized tomography (SPECT) to explore between group differences (highly creative versus less creative) in regional cerebral blood flow during the presentation of a creative cognition task (subtests of the Torrance Test). Task performance was correlated with greater activity in the right precentral gyrus (BA 6); the right anterior cerebellum; right postcentral gyrus (BA 3); right rectal gyrus (BA 11); right inferior parietal lobule (BA 40) and the right parahippocampal gyrus (BA 35) [52]. In the second experiment significant between group differences (high versus low creative) were found. The highly creative group showed increased cerebral blood flow in the right precentral gyrus (BA 6); right cerebellum; culmen; left middle frontal gyrus (BA 6 and 10); right frontal rectal gyrus (BA 11); left frontal orbital gyrus (BA 47), and left inferior temporal gyrus (BA 20) [53].

4. Structural imaging

Do the brains of creative people differ structurally from those who are less creative? Structural imaging studies explore relationships between brain anatomy and test performance. We found vastly fewer structural than functional studies, and the three papers we found were from our own lab (Table 2). We discuss these in some detail as they: (1) benefit from using precisely the same measures of divergent thinking across three different imaging modalities, (2) were conducted in large, healthy, young cohorts, and (3) controlled for important individual difference variables (i.e., age, sex, and intelligence) known to affect results. They simultaneously mea-

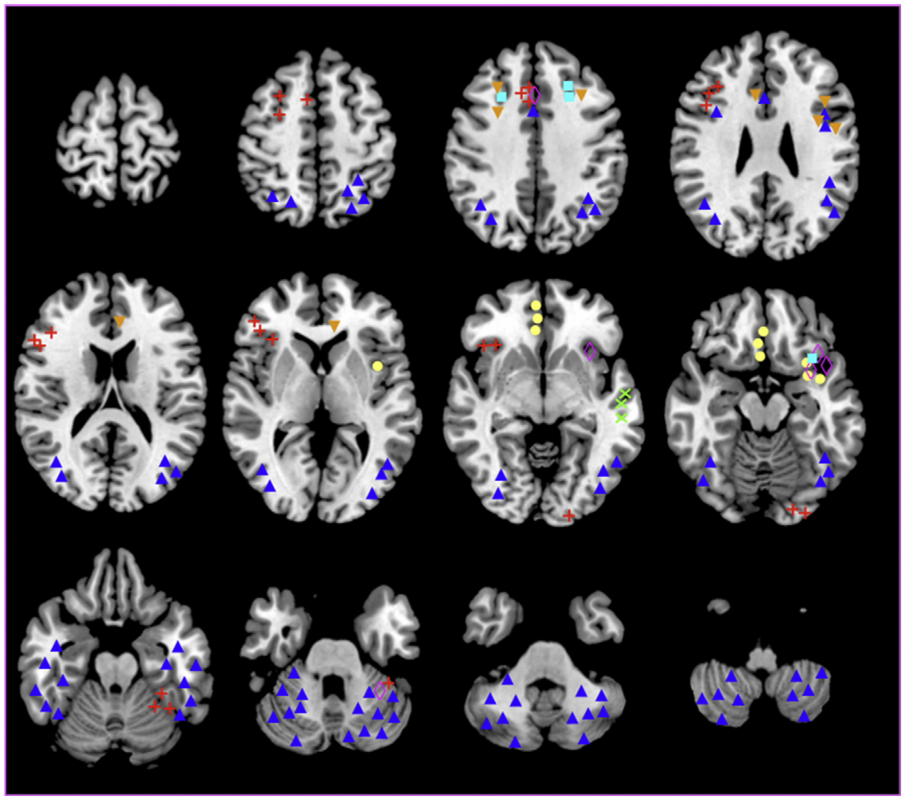

Fig. 1. Each of the coloured shapes in the figure above represents general areas of significant activation for each of the seven fMRI studies we reviewed. Coloured shapes correspond to each study as follows: Red cross = Fink et al. [22]; yellow circle = Asari et al. [43]; green 'X' = Jung-Beeman et al. [33]; cyan square = Goel and Vartanian [44]; blue triangle = Kowatari et al. [46]; pink diamond = Mashal et al. [47]; orange triangle = Howard-Jones et al. [45]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

sure well-validated intelligence, personality, and creative cognition variables and relate these to one another. In short, these studies provide a model for others in the field to emulate.

The first study used magnetic resonance imaging (MRI). This method employs standard T1 weighted images to segment the cortical mantle from regions bound by the pia mater and gray-white boundary [54]. In a sample of 61 young adults (mean age 24 and approximately half men and women), grey matter cortical thickness in a region in the lingual gyrus was negatively associated with a psychometric measure of creative cognition (indexed by three divergent thinking tasks), but was positively correlated with a different region in the right posterior cingulate [102]. This study also obtained participants' scores of self-reported achieved creativity (indexed by a questionnaire on activities and talents [55]). Here, too, the relationship between the measure and brain volume differed by brain region: lower grey matter volume was associated with higher achieved creativity in the left lateral orbito-frontal region, but higher volume correlated with achieved creativity in the right angular gyrus.

A second study examined white matter integrity through diffusion tensor imaging. This imaging method captures the three-dimensional diffusion of water in the tissues sampled within a voxel (volumetric pixel). Since axons are coated with fatty myelin, the diffusion of water is expected to be greater along the axon length rather than perpendicular to it (because the lipid boundary constrains the Brownian motion of water molecules). Fractional anisotropy is the measure of the extent to which water diffuses in a principal direction. If the fractional anisotropy value is high, it indicates that the white matter has a higher degree of structural coherence, with axon bundles being roughly parallel within a voxel and well insulated by myelin; low values are suggestive of lower structural coherence, with compromised axonal integrity or less myelination. It might seem intuitively true that since myelin is protective, 'more is better'. Indeed a significant positive correlation between scores on an intelligence test (WISC-III [56]) and degree of fractional anisotropy has been reported in a sample of 47 healthy children (aged 5–18) [57]. What about creativity?

In a sample of 72 healthy young adults, Jung et al. [101] found an inverse relationship between fractional anisotropy and creative cognition (indexed by four tasks). This negative association appeared in numerous regions within the left hemisphere including the inferior frontal white matter, and the superior longitudinal fasciculus. The same effect appeared in a small region within the right inferior frontal white matter and the anterior thalamic radiation. In this study intelligence was phenotypically positively correlated with creative cognition, and fractional anisotropy was significantly inversely associated with openness to experience. These two structural studies suggest that for creative cognition, less may be more.

The theme that 'more may be a bore' manifests in a third imaging study, not of brain structure, but of a brain metabolite. The metabolite N-acetyl-aspartate is the second most prolific concentrated metabolite in the brain (the first is glutamate) [58]. Although its role in the brain is not fully known, it contributes to myelin synthesis [59] and is a marker of neuronal health [60,61]. Decreases in concentration of N-acetyl-aspartate have been associated with early neuronal axon damage [62]. Jung et al. [64] probed the relationship between creative cognition and concentration of N-acetyl-aspartate in a sample of 56 healthy people using proton magnetic resonance spectroscopy. Spectroscopy is a useful diagnostic tool that can be tuned to read specific proton signals, in vivo, from metabolites that appear to be related to neuronal health and pathology [63].

In this spectroscopy study three divergent thinking tasks were ranked by three judges from whose scores a creativity index was derived [64]. Creative cognition was positively correlated with both verbal intelligence and openness to experience. N-acetyl-aspartate concentration was inversely correlated with creative cognition in the right anterior gray matter but positively correlated with creative cognition in the left anterior grey matter (i.e., the anterior cingulate gyrus). This study found a different pattern of association between the metabolite and creative cognition in post hoc analyses that took into account participants' verbal intelligence level (two groups divided by the sample verbal IQ mean). Thus, this was the first neuroimaging study to elicit the "threshold" effect, often seen in psychometric studies of creative cognition and intelligence, but this time dichotomized by brain–behavior relationships between N-acetyl-aspartate and creative cognition.

These structural and metabolite studies are consistent in showing that there is patterning within the relationships between brain and behavior. Total brain volume predicts intelligence moderately [65], but such a unitary predictor may be rare among brain correlates. In some brain regions, creative cognition is associated with more grey matter. But in many brain regions creative cognition is associated with less grey matter, lower white matter fidelity, and lower levels of N-acetyl-aspartate. In particular, structural studies revealed lower cortical thickness within the left orbitofrontal cortex associated with creative achievement, lower N-acetyl-aspartate levels in the left anterior cingulate associated with better divergent thinking (for subjects with IQ < 116), and lower white matter integrity in the left anterior thalamic radiation associated with better divergent thinking. Further, non-linear relationships, such as thresholds, may characterize the correlations between creative cognition and the brain.

Overall, the three structural studies point to a decidedly left lateralized, fronto-subcortical, and disinhibitory network of brain regions underlying creative cognition and achievement, consistent with theories of transient hypofrontality described elsewhere [66]. This network partially overlaps regions noted in fMRI studies including the left anterior cingulate [22,45,46], and the left inferior frontal cortex [45,47]. Thus, the left frontal lobe and underlying white matter remains a viable candidate underlying creative cognition.

5. Discussion

In our review of 45 published imaging studies of creative cognition (some of which contained more than one experiment), we found that nearly as many measures or tests were administered. The most frequently used test was the Alternate Uses Test [67]. The second most frequently used test was, the Remote Associates Test. The third most frequently used creative cognition measure was the Torrance Test (really a test battery from which researchers selected one or more subtests). It is clear from the literature we reviewed that authors are aware that task specificity is an irritant [5,68–70]. They are correct.

The 'criterion problem' in creativity may even have worsened since its discussion in 1982 by Amabile [5]. Measurement variation in creativity studies leads to an ineluctable confound in comparing across experiments. We cannot interpret, or integrate across, imaging studies that use such diverse creative cognition measures, most of unknown reliability and validity, and report activity in different brain regions of interest. It is impossible to know whether any results should be attributed to the measures, to the imaging modality or to unreliability in one or both. Further, the 'control' resting or baseline state may vary between studies because of experimental protocol differences between research groups. This exacerbates the already serious criterion problem.

The most urgent task ahead of creativity researchers, in our view, is to get 'down and dirty' with psychometrics. Until the psychometric properties of creative cognition are better characterized, imaging 'creativity' is not particularly useful.

There are several theories of creative cognition which imaging may help resolve in the future. These include hypotheses that creative cognition is associated with: the right brain; greater neural connectivity; neural efficiency; prefrontal function or low arousal. None of these can be tested without a reliable and valid index of creative cognition. Indeed, none of these theories were supported by a review of the literature: (1) creative cognition does not "reside" in the right brain – in contrast the best evidence so far supports a left frontal locus if any; (2) greater neural connectivity was both supported and refuted by various studies as was the concept of neural efficiency; (3) low arousal theories were *de rigueur* when "cortical idling" was popular, but now that this notion has been replaced with "inhibitory top-down control" [38,119], this notion is outdated. Even prefrontal theories of creative cognition must recognize the critical role of the "backal lobes" (collectively temporal, occipital, parietal) obviously necessary to creative cognition and well represented by several studies across all imaging modalities reviewed above.

We have some specific suggestions for advancing the field of creativity research. First we set out the aims, and then we discuss them in more detail.

(1) Goal: discover whether creative cognition is domain-specific. Action: test people phenotypically across many domains of creative production to quantify the common variance.
(2) Goal: increase reliability of the measure. Action: use exploratory factor analysis – administer diverse creative cognition test batteries to large samples ($N > 2000$).
(3) Goal: improve discriminant validity. Action: include intelligence (indexed by a reliable IQ-type test) and openness to experience (assessed by a reliable personality test) as covariates.
(4) Goal: improve ecological validity of the criterion. Action: use evolutionary theory to inform or guide test development.
(5) Goal: explore the aetiology of creative cognition. Action: administer creative cognition tests to genetically informative samples such as twins.
(6) Goal: improve confidence in our results. Action: increase sample sizes.
(7) Goal: increase comparability across studies. Action: converge on a common brain nomenclature.
(8) Goal: increase power of detecting effects. Action: move to study designs that use continuous measures rather than dichotomies such as case-control.

5.1. Domain-specificity

It is critical to know whether creative cognition is domain-specific or whether creative cognition is a 'super-ordinate' trait, like health, that perfuses many domains. This is an empirical question. The answer could be explored by administering creative cognition tests across many domains (such as art, music, problem solving, story-telling, cooking), on a representative community sample so that any common variance among tests can be quantified.

5.2. Reliability

Creative cognition measures in the literature have only modest reliability. Latent variable (or factor) analysis has the advantage of capturing common variance among separate tests within a battery while reducing the measurement error caused by method variance. Latent variable analysis was the key insight in intelligence research – a good example of a wild (seemingly intractable) higher-order cognitive construct tamed by psychometrics and made into a useful predictive tool. Intelligence is now measured with greater reliability than height or weight in a doctor's surgery [7] p. 50. A latent factor does not need to explain *all* the variance, under all contexts and conditions, to be a formidable ally in making sense of higher-order complex traits.

5.3. Discriminant validity

Scores on widely used measures of creative cognition correlate moderately and positively with intelligence test scores [64,71,72]. Since even elementary cognitive tasks (such as pressing a button when a light comes on) correlate somewhat with intelligence test scores [73–76], it is not surprising that creative cognition tests, which invite abstraction, reasoning, judgment, and innovation, are also positively associated with intelligence. If our goal is to explore creativity or neural correlates of creative cognition, such as electroencephalographic patterns that achieve discriminant validity beyond intelligence, a measure of intelligence is an essential covariate. For the same reasons, the personality dimension 'openness to experience' should be included in creativity studies as a covariate. Openness correlates positively with creative cognition (about $r = .50$). If we ignore it, our creativity criterion will lack discriminant validity.

If a creativity criterion is to be useful it must have real-work predictive validity. What constitutes such validity? The goal may not be to predict the next Mozart (trait extremes are usually too hard to predict because they require a constellation of co-incident rare events), but to predict the rank-order within a sample of people, on valid criteria. What criteria? Evolutionary theory may be helpful in guiding our thinking about when and why we are creative.

5.4. Ecological validity

The variation-selection process, which underpins all of evolutionary theory, appears to hold true with respect to creative cognition: indeed, the fact that creative achievers can be modeled by "a constrained, stochastic behavior accurately modeled as a quasi-random combinatorial process" [77] gives reason, purpose, and hypotheses to test, during test development. Similarly, it would be useful to design imaging experiments to test these ideas further. One approach may be to explore the performance and brain correlates of creative cognition across the ovulatory cycle (see, for example [78]). Another approach would be to test the social context of various creative productions within imaging studies (as done by [79]. Creativity likely has many uses. It may function adaptively as a signal of quality – to prospective mates ('choose me') and to parents ('feed me'). If so, then creative cognition will vary over the life-course [3,80–82]. Using the two examples above – mating and early childhood – creative productions may be more vigorous around these times. The imaging literature on creative cognition is focused on adults for good reasons – the youth of the imaging field, the cost of the experiments which are vulnerable to movement artifacts. Yet children are often intensely creative; learning how to nurture and maintain that creative cognition would be valuable to individuals and to society [83]. Young men and women show their creativity when they are romantically engaged [79]. Away from the world of patents and published novels how would individual differences in creative cognition show among a population of Hunter-Gatherers? It may be useful to keep in mind the likely ancestral functions and types of creative display as we develop creative cognition tasks.

Humans are the most creative animals (assessed by the absolute number of innovations) but not the only creative animals. It may be useful to consider the nature and function of creativity in other lineages (such as passerine song production, bowerbird bowers [84,85]. Creativity may arise in several lineages as a result of convergent evolution (different genetic pathways leading to similar phenotypes). The usefulness of attending to other species may be mostly conceptual but it could also lead to new empirically testable hypotheses.

5.5. Aetiology

Genetically informative samples allow quantification of the genetic and environmental contributions to the traits under consideration. They also allow researchers to discover patterns of relationships (phenotypic and genetic correlations) in a multivariate design. We only found one study (an unpublished diploma thesis that was both comprehensive and methodologically impressive [86] in which the investigator focused on the aetiology of creativity through a behavioral genetic design. In a sample of 53 monozygotic and 43 dizygotic twin pairs (55 males, 212 female) Penke found that the genetic contribution to creativity (as measured by the T-88 line drawing completion task; [87]) was around 60%. This is consistent with reported the heritability of intelligence in adults [88,89] and slightly higher than that reported for the personality trait openness to experience [90] in a similar age group.

In this report, neuroimaging is our central concern, though we hope that more studies will replicate the biometrical parameters (partitioning the variance in individual differences between genetic and non genetic sources) of creativity. Understanding more about the genesis of creativity will help us identify candidate genes for future molecular genetic work. It would also be useful to learn about the genetic contribution to the outcome of various imaging modalities (for example 'what is the genetic contribution to individual differences that show up in diffusion tensor images?' (see, for example [91]).

5.6. Sample size

Neuroimaging is costly (varying between imaging modalities); the effect is reflected in the sample sizes of the studies we reviewed. The largest sample was $N = 117$ [92] the smallest was $N = 8$ [45]. An estimate of the power to detect the effects reported would be useful common practice in our field. Since our results depend on the sample size, as well as the product of the reliability of the measures and the reliability of the imaging procedure, information about these parameters are critical for interpretation. Collaborations which can afford larger samples would help the field.

5.7. Nomenclature

Brain researchers do not all use exactly the same nomenclature to describe regions of interest. Our position is somewhat analogous to written English before the printing press was invented and before Samuel Johnson's (1709–1784) dictionary laid the foundation for standardized spellings. It would be useful to have a standardized nomenclature with regional specificity akin to global positioning system co-ordinates. At present it is hard to know when or if studies are showing results for the same brain regions because the areas are often anatomically under-specified or because they are described differently among diverse laboratories. The inclusion of Talairach or MNI co-ordinates in results tables is a good first step in localizing findings to particular brain regions.

5.8. Study design

Many of the studies we reviewed employed case-control designs (contrasting people with observed or expected high creativity with those of observed or expected low creativity). We can assume that creativity has an underlying, somewhat normally distributed character [93]. Designs that include the quantitative, continuous nature of the trait are more statistically sensitive and powerful than designs that depend on dichotomous data. We hope that there is a move toward continuous scales of creative cognition.

6. Limitations

We aimed to include all imaging studies of creative cognition in our review but we most certainly overlooked some publications. We welcome notices of published studies omitted inadvertently. We did not review studies published in languages other than English. This excluded publications in Russian, in particular; we regret this shortcoming because there is great strength in creative cognition research among Russian-speaking scholars. We focused here explicitly on creativity; our attention to related phenomena such as insight [33,94–99] was limited. Our concern about measurement diversity and reproducibility (mentioned above) was the reason for this restriction.

7. Conclusion

Our original intention was to read broadly in the literature of creative cognition that included a neuroimaging component, then to integrate the results across studies as we had done previously for neuroimaging of intelligence [100]. We knew that task specificity would present a confound, but we did not anticipate the magnitude of the problem. We realised that basic psychometric work is essential for the field. Without it, we cannot know what we are imaging. We have made several suggestions for developing creativity research. We hope to implement them and that others may also find them useful. Like others, we have a hunch that when we speak about creativity, we refer to something measurable that is not perfectly captured by related cognitive abilities. We will find out whether this intuition is right or wrong by testing it empirically with the rich set of tools developed by psychometricians and neuroscientists.

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