Elements of creative thought: Investigating the cognitive and neural correlates of association and bi-association processes

Mathias Benedek [a,*], Julian Jurisch [a], Karl Koschutnig [a], Andreas Fink [a], Roger E. Beaty [b]

[a] *Institute of Psychology, University of Graz, BioTechMed, Graz, Austria*
[b] *Department of Psychology, Pennsylvania State University, USA*

A B S T R A C T

Creative thinking relies on the ability to make remote associations and fruitfully combine unrelated concepts. Hence, original associations and bi-associations (i.e., associations to one and two concepts, respectively) are considered elementary cognitive processes of creative cognition. In this work, we investigated the cognitive and brain mechanisms underlying these association processes with tasks that asked for original associations to either one or two adjective stimuli. Study 1 showed that the generation of more original associations and bi-associations was related to several indicators of creativity, corroborating the validity of these association performances as basic processes underlying creative cognition. Study 2 assessed brain activity during performance of these association tasks by means of fMRI. The generation of original versus common associations was related to higher activation in bilateral lingual gyri suggesting that cued search for remote representatives of given properties are supported by visually-mediated search strategies. Parametric analyses further showed that the generation of more original associations involved activation of the left inferior frontal cortex and the left ventromedial prefrontal cortex, which are consistently implicated in constrained retrieval and evaluation processes, and relevant for making distant semantic connections. Finally, the generation of original bi-associations involved higher activation in bilateral hippocampus and inferior parietal lobe, indicating that conceptual combination recruits episodic simulation processes. Together, these findings suggest that the generation of verbally cued, original associations relies not only on verbal semantic memory but involves mental imagery and episodic simulation, offering new insights in the nuanced interplay of memory systems in creative thought.

1. Introduction

In recent years, an increasing number of studies have explored brain activity in diverse creative activities ranging from creative problem solving to artistic activities (Abraham, 2018; Jung and Vartanian, 2018). One promising approach in this field is to identify basic cognitive processes that are assumed to be broadly relevant to different forms of creative thought (Benedek and Fink, 2019). Considering the role of memory, for instance, a long-standing notion in the cognitive science of creativity holds that creative idea generation requires connecting unrelated concepts, which is achieved by finding original associations and combining them in a meaningful way (Mednick, 1962). Creative thinking hence relies on the generation of original associations (i.e., remote associations to one concept) and on the generation of bi-associations (i.e., links between two concepts), which corresponds to the broad capacities of conceptual expansion and conceptual combination, respectively (Ward et al.,

1997). Here, we sought to investigate the cognitive and neural mechanisms underlying these two elementary processes of creative thought. To this end, we devised tasks assessing the generation of original associations and bi-associations in the context of word associations. In a first study, we explored the criterion validity of these association tasks with respect to creativity, and in a second study, we examined the brain activation related to these association abilities by means of fMRI.

1.1. Expanding concepts: the generation of original associations

For many routine cognitive activities, it is crucial to quickly retrieve relevant, closely related information in order to produce appropriate responses. Creative thought, however, typically requires avoiding common, dominant associations in order to produce original responses. The generation of associations can occur either via spontaneous, free-associative and or via goal-directed, controlled mechanisms (Beaty

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et al., 2014; Benedek and Jauk, 2018; Sowden et al., 2015). Free association reflects the basic spreading of activation in semantic networks, whereas controlled association generation reflects a goal-directed process of constrained recall considering specific search cues. Early conceptions assumed that original associations produced by creative people are the result of a deviant organization of memory (Mednick, 1962). This view has been challenged by the observation that creative people do not only typically find more uncommon (i.e., original) associations but also more common associations compared to control groups when explicitly asked to do so (Merten and Fischer, 1999). In fact, creative people were found to exhibit very similar free association patterns of increasingly original associations but they produced responses much more fluently, thus resulting in more original associations within a given time (Benedek et al., 2012; Benedek and Neubauer, 2013). Moreover, creative cognitive potential in terms of divergent thinking ability is substantially related to higher intelligence and executive control (Benedek and Jauk, 2019; Chrysikou, 2018), with particularly high correlations typically observed with broad retrieval ability (Gr), suggesting that creative idea generation relies on highly effective search and retrieval mechanisms (Avitia and Kaufman, 2014; Forthmann et al., 2019; Silvia et al., 2013).

A few studies have begun to shed light on the brain mechanisms related to the generation of original associations. One fMRI study asked participants to generate verb associations to nouns and cued them to think creatively in half of the trials (Green et al., 2015). The cued trials resulted in more semantically distant responses (as assessed by latent semantic distance analysis), and individual differences in cued association performance were related to several established measures of creative potential in a separate behavioral study (Prabhakaran et al., 2014). Moreover, Green et al. (2015) found that the generation of remote associations was related to increased brain activity in a left-lateralized frontal network including medial prefrontal cortex and inferior frontal gyrus, as well as occipital (cuneus and lingual gyrus) and cerebellar regions. A parametric analysis further revealed that brain activity in a region of interest in the left frontopolar cortex linearly increased with the semantic distance of responses, suggesting that this frontopolar region is implicated in the generation of particularly remote associations.

Another study examined the effect of conceptual interference in the verb generation task and found that high conceptual constraints resulted in less semantically distant responses, which corresponded to increased brain activity in bilateral precuneus, angular gyrus, posterior cingulate, left middle frontal gyrus, and lingual gyrus (Beaty et al., 2017). Moreover, generative constraints were further related to increased functional connectivity between a left executive control network and anterior default network, suggesting that coupling between these executive and default network regions plays a role in overcoming conceptual interference in creative thought (Beaty et al., 2016). Yet another fMRI study compared brain activation during the generation of free association chains (i.e., a sequence of consecutively related word pairs) with performance in word fluency and category fluency tasks (Marron et al., 2018). Free association performance was related to higher divergent thinking ability and involved higher activation in a left-lateralized network including the medial prefrontal cortex, posterior cingulate, temporoparietal junction, as well as inferior, middle, and superior frontal gyrus.

In the context of creative idea generation, some studies have looked at the process of passive conceptual expansion, assessed by the evaluation of more versus less original ideas, and active conceptual expansion, assessed by actual creative idea generation, and found consistent involvement of the temporal poles, inferior frontal gyrus and frontopolar cortex (Abraham et al., 2012; Abraham et al., 2018; Kröger et al., 2012). Together, these studies show that the generation of original associations is a valid low-level process of creative cognition that implicates several regions within the default network (DN) and executive control network (ECN), as well as visual networks. Brain activation in and functional coupling between these large-scale brain networks have been consistently related to various forms of creative cognition (Beaty et al., 2016;

Zabelina and Andrews-Hanna, 2016).

1.2. Combining concepts: the generation of original bi-associations

Creativity theories also emphasize that creative thinking requires uncovering associations that connect two unrelated concepts in a fruitful way. The generation of such an associative link can be called *bi-association* (or *bisociation*, see Koestler, 1964), double association, or associative combination. While an original association represents a distant leap within one concept's association network, a bi-association establishes a link, or identifies a point of overlap, between the association networks of two largely unrelated concepts. Mednick (1962) devised the Remote Associates Test (RAT) to assess individual differences in the ability to flexibly combine concepts. The RAT presents three unrelated cue words and requires finding a fourth word offering a link to all cues in terms of building compound nouns with each (e.g., blue, cottage, cake; response: cheese). Process analyses of RAT performance have shown that it commonly involved incrementally constrained search processes, where participants make an association to one cue and then evaluate its fit to the other cues (Smith et al., 2013). Hence, one approach to bi-association generation may be to generate original associations to one concept and evaluating its semantic relation to the other. Notably, the validity evidence for the RAT is mixed as it typically shows high correlation with verbal intelligence (Lee and Therriault, 2013) and lower associations with creativity indicators (Taft and Rossiter, 1966), which may be related to the fact that RAT solutions only represent linguistic links in the form of compound nouns (e.g., blue cheese, cheese cake), but do not necessarily establish a semantic link between these concepts. Other work has tapped more directly into the process of bi-association using tasks asking for associative combinations of two unrelated nouns or for humorous explanations of arbitrary word combinations (e.g., "yoga-bank" or "cereal-bus", which showed correlations with established measures of creative potential (Benedek et al., 2012; Nusbaum et al., 2017). Interestingly, creative people also judge unrelated concepts as more semantically related, suggesting that they are very sensitive to subtle associative links between concepts (Benedek et al., 2017; Rossmann and Fink, 2010).

While several studies have examined the brain activation related to the generation of original associations, neuroscientific investigations of the bi-association process are more sparse. Some works studied brain activation when solving the RAT, but they typically focused on the distinction between subjective experiences of insight versus non-insight problem solving (Jung-Beeman et al., 2004). Other studies tapped into similar processes when studying relational integration (Christoff et al., 2001) or analogical reasoning (Green et al., 2010), which were related to brain activity in rostrolateral prefrontal cortex (PFC). Bendetowicz et al. (2017) developed an associative version of the RAT (i.e., solutions represent semantically related terms rather than compound words that share one term) and found that higher performance in this task was related to lower gray matter volume in the left rostrolateral PFC and in the left inferior parietal lobule. Another study by Bendetowicz et al. (2018) on patients with focal frontal lesions found that damage to the right medial PFC affected their ability to generate remote associations, whereas damage to the left rostrolateral PFC spared remote association ability but impaired the associative combination ability as measured with the associative RAT. Further fMRI studies found that the generation of novel ideas versus recalled ideas implied higher activation of the left anterior inferior parietal cortex (Benedek et al., 2014b; Benedek et al., 2018), which was attributed to this regions' role in cross-modal semantic integration (Binder et al., 2009). These findings offer first insights into the brain structures relevant to associative combination processes but, to date, an investigation contrasting association and bi-associations processes is still missing.

1.3. Aims of this study

The present study aimed to investigate neurocognitive mechanisms

underlying the generation of original associations and bi-associations. In a first behavioral study, we developed tasks that assess these processes separately and explored their validity with respect to established measures of creativity. In a subsequent fMRI study, we measured brain activity during the generation of original associations and bi-associations relative to the generation of common associations. This work extends available research by assessing brain activation of two elementary cognitive processes central to creative cognition within the same paradigm, which allows testing activation differences between the generation of original versus common associations, and between the generation of original bi-association versus single associations. Based on the available literature we hypothesized that conceptual expansion processes, which are reflected in the generation of original associations, recruit regions of DN and ECN, including the medial and lateral prefrontal cortex, while conceptual integration processes, which are specific to the generation of bi-associations, may be related to brain activity in the left rostrolateral PFC and left inferior parietal cortex.

2. Study 1: behavioral investigation

2.1. Method

2.1.1. Participants

The final sample consisted of 102 participants (62 females), aged between 18 and 38 years ($M = 25.4$; $SD = 4.1$). Another five participants had been excluded from further analyses due to invalid performance in the association tasks (i.e., generation of other word types than nouns, or missing data >25%). All participants gave written informed consent.

2.1.2. Tasks and materials

2.1.2.1. Association tasks.
This study involved three association tasks, requiring the generation of either common associations, original associations, or bi-associations. All tasks used adjectives as stimuli and asked to generate a semantically related noun (either a single or multi-word term). In the *common association* task (Com-Assoc), participants should find a highly related concept to a given adjective, one that "may first come to mind to most people" thus representing a common association (e.g., red: blood). In the *original association* task (Orig-Assoc), participants should find a remotely related concept to a given adjective, one that "only few people would think of" and that "represents an original association" (e.g., red: ketchup stain). These association tasks were inspired by previous studies comparing free versus individual associations (Merten and Fischer, 1999), associations versus dissociations (Benedek et al., 2012), or uncued versus cued verb associations (Prabhakaran et al., 2014). In the *bi-association* task (Bi-Assoc), two adjectives were presented and participants should find a concept that is semantically related to both cues and links them in an original way (e.g., red - round: clown nose). Specifically, participants were asked to "think of a concept for which both adjectives (characteristics) apply", and, if they have time to generate different responses, to "choose the more original one". This task requires a semantic integration of two largely unrelated concepts and thus is similar to the associative version of the Remote Associates Test that used three cue words (Bendetowicz et al., 2017), and to the association combination task that asked to find many bi-associations for given noun pairs (Benedek et al., 2012). Importantly, generating a balanced bi-association for two largely unrelated stimulus concepts cannot simply be achieved by producing a common association to one of the stimuli but rather requires finding a concept that is somewhat remote yet reasonably related to both stimuli. Hence, performance of the Bi-Assoc task is thought to involve remote association processes similar to the Org-Assoc task, but additionally requires conceptual integration processes.

The stimulus words were taken from a German word corpus (http://corpora.uni-leipzig.de/de). We selected 60 adjectives that are frequent in German language (frequency class of 17 or lower, meaning that each word is not more than 2^{17} times infrequent than the most frequent German word "der" [the]) and that are largely unrelated (i.e., not listed as synonym to any other adjective). With the 60 adjectives, we created 30 trials for each task (i.e., 90 trials in total): half of the adjectives were randomly assigned to the Com-Assoc task and the other half to the Orig-Assoc task, and all adjectives were used to build 30 adjective-pairs for the Bi-Assoc task. For the adjective pairs, we generally strived to choose adjectives with low semantic similarity. The average cosine similarity of the adjective pairs (based on latent semantic analysis using the dewak100k_lsa corpus, a German LSA-type space covering 300 dimensions and containing vectors for 100,000 different words) was 0.32 ($SD = 0.15$; range = 0.07 - 0.61). A full list of all stimuli is given in the Supplemental Material.

The tasks were presented on a computer screen and responses were written on a response sheet. Participants first performed the single association tasks (Com-Assoc and Orig-Assoc) in an inter-leaved fashion. The stimuli were presented for 5s, during which the participants thought of an association response (i.e., thinking period). If the stimulus word was underlined they should think of an original association, but if it was not underlined they should think of a common association. The Com-Assoc and Orig-Assoc conditions switched predictably every three trials to reduce potential switching costs. After the thinking period, a blank screen was presented for 5 s indicating the response period during which responses were written down. The subsequent Bi-Assoc task followed the same procedure, except that the thinking period was 8s to allow enough time for the more complex task of generating associations for two cue words.

Valid responses (i.e., not missing, noun responses) were obtained in 96% of the Com-Assoc trials, 92% of the Orig-Assoc trials, and in 91% of the Bi-Assoc trials. All responses were rated by five raters. Responses of the single association tasks (Com-Assoc and Orig-Assoc) were pooled and then rated for creativity using a four-point scale (0–3), with higher ratings given to responses that were judged as task-appropriate and original (i.e., responses that are semantically related to the stimulus and potentially reflect clever, surprising, or humorous associations). Invalid or missing responses were assigned a zero rating. Quality of responses in the Bi-Assoc task was also evaluated on a four-point rating scale, with ratings of 0 given to responses that were unrelated to both cues, ratings of 1 given to responses that mostly reflect only one cue, ratings of 2 are given to responses that reflected both cues well, and ratings of 3 given to highly original responses that reflect both cues well. All raters were trained in a common session but they rated responses independently. Inter-rater-reliability was good for the single association tasks (ICC = 0.80) and acceptable for the Bi-Assoc task (ICC = 0.75).

2.1.2.2. Validation measures.
Task performance was validated with respect to common indicators of creativity including divergent thinking (DT) ability, real-life creative behavior, and creative personality. DT ability was assessed with the alternate uses task, which asks to name all the creative uses one can think of for everyday objects. Participants completed four tasks (rope, car tire, knife, pillow) of 2 min each. All responses were rated for creativity by five raters on a four-point rating scale (0–3) with higher ratings given to responses that were judged as both novel and effective (responses are task-appropriate and clever, surprising, or humorous; Diedrich et al., 2015; Runco and Jaeger, 2012). Inter-rater-reliability was acceptable to good (ICC = 0.79). DT creativity was defined as the average creativity rating of three most creative responses as determined by the average across raters (max-3 scoring; for similar scorings see, Benedek et al., 2013; Silvia et al., 2008). Additionally, we measured DT fluency defined as the number of responses in the DT tasks.

Real-life creative behavior was measured with the activity scale of the Inventory of Creative Activities and Achievements (ICAA; Diedrich et al., 2018). This scale asks how often specific creative activities have been performed in the last ten years (0 = never, to 4 = more than 10 times),

covering eight creative domains (e.g., literature, music etc.) with six items each. The internal consistency of the ICAA creative activities was high (ICC = 0.90).

Openness to new experiences, the most consistent factor of creative personality (Feist, 1998), was assessed with 12 openness items from the NEO-FFI (Borkenau and Ostendorf, 1999). Since all tasks required written responses, we further assessed writing speed to examine potential effects of common method bias. Participants were asked to write down as many number words (1–10) as possible in ascending and descending sequence within 20 s (i.e., one – two – three …) and the total number of written words was used as index of writing speed (Benedek et al., 2012).

We further assessed broad retrieval ability (Gr) and fluid intelligence (Gf), which have been shown to be consistently correlated with creative potential (Jauk et al., 2014; Silvia et al., 2013). Gr was assessed with two letter fluency tasks (F, N), two category fluency tasks (professions, types of sport), and two free association tasks (pure, funny; these adjectives were not part of the association tasks). Participants generated as many responses as possible within 1 min per task. The response fluency scores of all tasks were averaged to obtain a total Gr score. Gf was assessed with a shorted version of the Ravens Advanced Progressive Matrices (18 even-numbered items; 10 min task duration; Raven et al., 1962) and with the 20-item number series task from the intelligence structure test (IST, 2000 R; Liepmann et al., 2007). The solution rate in both tasks was averaged to obtain a total Gf score.

2.1.2.3. Data and code availability. Data and code of Study 1 and 2 are available upon request from the authors to be further used for scientific purposes. These conditions comply with the institutions ethics approval and the requirements of the funding body.

2.1.2.4. Procedure. Participants took part in the experiment individually or in small groups of up to five persons per session. All tasks were administered in a fixed sequence: writing speed, single association tasks, bi-association task, openness, DT, Gr, Gf, ICAA activities. The session took about 90 min in total. The procedure was approved by the local ethics committee.

2.2. Results and discussion

Table 1 presents descriptive statistics and inter-correlations of the three association tasks and all validation measures. As expected, the Orig-Assoc task elicited more creative association responses ($M = 1.64$, $SD = 1.20$) compared to the Com-Assoc task ($M = 1.35$; $SD = 1.07$; $t[101] = 6.58$, $p < .001$, $d = 0.64$), supporting the general effectiveness of the creativity instruction. This finding is consistent with previous work showing that the explicit instruction to "be creative" increases the creativity of responses (and not just the divergence of responses; Weinberger et al., 2016) as has been repeatedly demonstrated for divergent thinking tasks (Acar et al., 2020; Said-Metwaly et al., 2020) as well as for more elementary association tasks (Merten and Fischer, 1999; Prabhakaran et al., 2014). For the Bi-Assoc task, an average rating of 1.61 was observed. Specifically, responses were evaluated with 2 or higher in 61.2% of ratings (67% of valid responses), suggesting that the task was challenging, but still yielded task-appropriate responses reflecting both cues in the majority of cases.

Performance in the Com-Assoc task was only correlated with Orig-Assoc performance but with none of the validation measures. In contrast, Orig-Assoc performance showed substantial correlations with DT creativity, DT fluency, openness, Gr and Gf (see Table 1). These findings replicate the observation that single association tasks, which do not reflect response fluency (cf. Benedek et al., 2012), are only indicative of creativity when performed under "be creative" instructions (Prabhakaran et al., 2014). Similarly, performance in the Bi-Assoc task was significantly correlated with all validation measures including DT creativity, DT fluency, creative activity, openness, Gr, and Gf.

Hence, validity evidence for Orig-Assoc and Bi-Assoc tasks was obtained with respect to various established indicators of creativity such as divergent thinking ability, real-life creative behavior, and openness (Jauk et al., 2014). Correlations with Gr and Gf are consistent with the broad evidence on the executive nature of creative thought (Benedek et al., 2014c; Silvia et al., 2013). Interestingly, Gr tended to be stronger correlated with Orig-Assoc than with Bi-Assoc, whereas Gf tended to be higher correlated with Bi-Assoc than with Orig-Assoc. These differences may highlight relatively higher demands on cued retrieval from semantic networks versus complex semantic integration and evaluation processes involved in the Orig-Assoc and Bi-Assoc tasks, respectively. Notably, despite the substantial correlation between Orig-Assoc and Bi-Assoc, they predicted unique variance in openness ($\beta = 0.21$, and 0.24, $p < .05$, respectively), but in none of the other validation measures, suggesting that they capture at least partly complemental capacities. Taken together, these findings indicate that original association and bi-association performances reflect elementary cognitive processes of creative cognition. In study 2, we used these association tasks to study brain processes related to the generation original and bi-associations relative to common associations.

3. Study 2: fMRI investigation

3.1. Method

3.1.1. Participants

An independent sample of 44 University students (26 female), aged between 19 and 36 years ($M = 24.34$; $SD = 4.35$), participated in study 2. Two additional participants had been excluded from further analyses, one because of aborting the scanner session due to indisposition, and one because of insufficient language skills (non-native speaker). Participants were recruited by local advertisements and gave written informed consent. They were either paid or participated for partial course credit.

Table 1
Descriptive statistics and correlations of all measures.

	M	SD	1	2	3	4	5	6	7	8	9
1 Com-Assoc	1.07	0.11	–								
2 Orig-Assoc	1.20	0.21	**.33**	–							
3 Bi-Assoc	1.62	0.18	.17	**.44**	–						
4 DT Creativity	1.61	0.32	.15	**.38**	**.25**	–					
5 DT Fluency	8.03	2.55	.12	**.30**	**.22**	**.37**	–				
6 C-Activity	1.42	0.52	.05	.17	**.20**	**.25**	.17	–			
7 Openness	2.92	0.51	.12	**.32**	**.33**	**.22**	.13	**.40**	–		
8 Gr	13.26	2.04	.17	**.42**	**.29**	**.39**	**.51**	.18	**.25**	–	
9 Gf	11.54	2.78	.07	**.31**	**.36**	.07	.06	.07	.16	.16	–
10 W-Speed	12.41	1.75	.10	-.08	-.06	.01	.04	-.01	**.19**	.09	.09

Notes. Com-Assoc = common association, Orig-Assoc = original association, Bi-Assoc = bi-association, DT = Divergent thinking, C-Activity = Creative activities, Gr = Broad retrieval ability, Gf = fluid intelligence, W-Speed = Writing speed. For $n = 102$, correlations of $r \geq 0.19$ are significant at $p < .05$, correlations of $r \geq 0.25$ are significant at $p < .01$, and correlations of $r \geq 0.31$ are significant at $p < .001$. Significant correlations ($p < .05$) are indicated in bold.

3.1.2. Experimental task and procedure

Participants performed the three association tasks (Com-Assoc, Orig-Assoc, Bi-Assoc) described in Study 1. Outside the scanner, participants received thorough task instructions, including ten practice trials. In the scanner, they completed a total of 75 trials, including 25 Com-Assoc trials, 25 Orig-Assoc trials, and 25 Bi-Assoc trials (a full list of all stimuli is given in the Supplemental Material). Trials were grouped in five blocks of five trials each to reduce task switching demands. Task blocks were presented in one out of two quasi-randomized sequences. At the beginning of a block, a task cue (Common association, Original association, Combined association) was presented at the middle of the screen for 5 s. Then, each trial started with a *fixation* period, presenting a white fixation cross on black background jittered between 3 and 5 s, followed by the *thinking* period (Com-Assoc, and Orig-Assoc: 5 s; Bi-Assoc: 8 s), presenting the task stimulus in white letters on black background. In the Bi-Assoc task, the stimulus consisted of two adjectives (e.g., red – round), whereas in the single association tasks (Com-Assoc, and Orig-Assoc) the stimulus consisted of one adjective that was presented two times (e.g. red – red) in order to keep visual demands similar across all tasks. During the *thinking* period participants were asked to think about a response but not verbalize it; when they found a solution before timeout, they were asked to think of an even better response in the remaining time (Com-Assoc: more common association; Orig-Assoc and Bi-Assoc: more original response). After this *thinking* period, the stimulus appeared in green letters for 4 s (*response* period), prompting the participants to vocalize their response (Benedek et al., 2019; Fink et al., 2009). Responses were recorded with an MRI-compatible microphone and transcribed by an experimenter outside the scanner room. The whole task took about 20 min. Fig. 1 illustrates the task procedure. The scanner session included a field-map scan, a T1 scan, and performance of the described tasks and another short task unrelated to this study (Benedek et al., 2018). The procedure was approved by the local ethics committee.

3.1.3. fMRI data acquisition

Whole brain imaging was performed on a 3T Siemens Skyra MRI system (Siemens Healthineers, Erlangen, Germany) using a 32-channel head coil. Structural brain images were obtained using a T1-weighted 3D-MPRAGE sequence (TR = 1560 ms, TE = 2.07 ms, flip angle = 9°, 176 sagittal slices, 1 × 1 × 1 mm, FoV = 256 × 256 mm, TI = 900 ms). BOLD-sensitive T2*-weighted functional images were acquired using a single shot gradient-echo EPI pulse sequence (TR = 2400 ms, TE = 30 ms, flip angle = 90°, 39 axial slices, 3 × 3 × 3 mm, distance factor 20%, FoV = 240 × 240 mm, interleaved slice ordering). The first two volumes were automatically discarded to allow for T1 equilibration effects. head. In addition to structural and functional images, a dual-echo gradient echo field map (TR = 403 ms, delta TE = 2.46 ms) was recorded for distortion correction of the acquired EPI images. Head motion was restricted using firm padding that surrounded the head.

Visual stimuli were presented using the software Presentation (Neurobehavioral Systems, Albany, CA) on an LCD monitor positioned at the top end of the scanner bore, viewed through a mirror attached to the head coil. Verbal responses were recorded by means of an MRI-compatible noise cancelling microphone (FOMRI-III; Optoacoustics, Mazor, Israel) also attached to the head coil.

3.1.4. Data analysis

3.1.4.1. Behavioral analysis.
All responses were transcribed and checked. Trials with missing responses or with responses that were not nouns were flagged as invalid and excluded from further analyses. For tests of performance differences between Com-Assoc and Orig-Assoc, all single association task responses were pooled and evaluated for originality by three independent judges on a four-point rating scale ranging from 0 (common) to 3 (highly original) following standard rating procedures (Benedek et al., 2013; Silvia et al., 2008). Inter-rater reliability was good (ICC = 0.81) and creativity ratings were averaged across raters.

3.1.4.2. fMRI data analysis.
MRI data were converted to BIDS format ensuring standardization and anonymization of data (Gorgolewski et al., 2016), and verified using the BIDS validator (http://bids-standard.github.io/bids-validator/). Data were preprocessed with the preprocessing pipeline *fMRIPrep* 1.3.2 (Esteban et al., 2019) using the default processing steps. In summary, each structural image was corrected for intensity non-uniformity and skull-stripped. Spatial normalization to the ICBM 152 Nonlinear Asymmetrical template version 2009c was performed through nonlinear registration with antsRegistration (ANTs 2.2.0). Functional data was corrected for susceptibility distortions based on a coregistered field map. Slice-timing correction was performed using 3dTshift from AFNI 20160207 (Cox and Hyde, 1997). Based on the estimated susceptibility distortion, an unwarped BOLD reference was calculated for a more accurate co-registration with the anatomical reference. The BOLD reference was then co-registered to the T1w
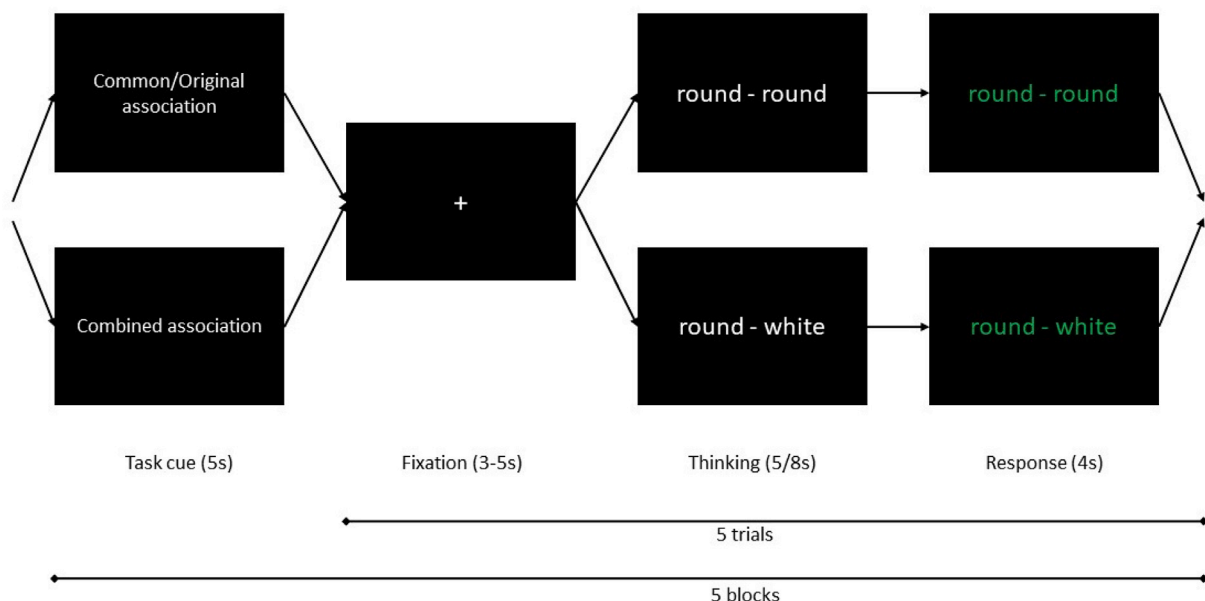

Fig. 1. Procedure of the scanner tasks involving the common association task (Com-Assoc), original association task (Orig-Assoc) and bi-association task (Bi-Assoc).

reference using *bbregister* and resampled to MNI152NLin2009cAsym standard space. Then, a high-pass filter (128s cut-off) was applied. Several time-series of potential confounds were calculated including frame-wise displacement, global signals and physiological regressors to allow for component-based noise correction (CompCor; Behzadi et al., 2007). Finally, functional data were smoothed with a 6-mm full-width at half-maximum Gaussian kernel in SPM 12 (Wellcome Department of Imaging Neuroscience, London, UK).

Effects were estimated using the General Linear Model (GLM) as implemented in SPM 12. At the first level, three regressors of interest were included, representing the generation periods of valid trials in the three association tasks. The three regressors were modelled with boxcar functions with the length of task duration convolved with the canonical hemodynamic response function (HRF). We further included the response period and twelve control parameters derived during pre-processing as regressors of no interest to control for susceptibility effects related to response generation and head motion. Linear contrasts were used to obtain subject-specific estimates for each effect, which were entered into a second-level analysis treating subjects as a random effect.

We investigated the brain mechanisms underlying the search for remotely related concepts (i.e., the process of conceptual expansion) by contrasting the brain activation during the generation of original versus common association (Orig-Assoc > Com-Assoc). Linear effects of association remoteness were further analyzed with a parametric analysis considering the originality of association responses. In a next step, we examined the process of conceptual combination/integration by contrasting brain activation during the generation of original bi-associations versus original single associations (Bi-Assoc > Orig-Assoc); for the sake of completeness, we also report the contrast of bi-association versus common association generation (Bi-Assoc > Com-Assoc). Additionally, we performed low-level task contrasts by contrasting each task individually against implicit baseline (findings from these complementary analyses are reported in the Supplemental Material, Tables S1–S3). Whole-brain effects were inclusively masked with a binary gray matter mask estimated based on the SPM12 gray matter tissue map (x > 0.2), and effects are reported when they were significant at voxel-level ($p < .05$, FWE-corrected for multiple comparisons) and cluster size was ≥ 3.

3.2. Results and discussion

3.2.1. Task performance

Participants generated valid responses in 96% of the Com-Assoc trials, 92% of the Orig-Assoc trials, and in 92% of the Bi-Assoc trials. The responses in the Orig-Assoc task were again significantly more original ($M = 1.55; SD = 0.30$) than in the Com-Assoc task ($M = 0.83; SD = 0.19; t$ [43] $= 13.90, p < .001; d = 2.05$), supporting the effectiveness of the task instructions to generate original versus common associations.

3.2.2. Brain activation related to the generation of original associations

We examined task-specific brain activation effects by means of the task contrast Orig-Assoc > Com-Assoc. The generation of original versus common associations was associated with higher brain activation in focused clusters of bilateral lingual gyrus (Table 2, and Fig. 2). This finding is consistent with previous research, reporting brain activation in lingual gyri during word association tasks (Andreasen, 2012; Green et al., 2015) as well as during more complex forms of divergent thinking (Beaty et al., 2017; Fink et al., 2015). The lingual gyrus plays an important role for vision encoding and retrieval especially in the context of words and for the generation of visual mental images (Kosslyn et al., 1997; Leshikar et al., 2012; Machielsen et al., 2000). These findings suggest that the generation of original associations for adjective words may actually involve visually-mediated retrieval strategies. While searching for *common* representatives of adjectives may be achieved by simple recall of primary associations from verbal semantic memory (e.g., round: ball), finding original representatives of properties (e.g., round: Frisbee) may be more effective when search is cued by abstract mental images of the

Table 2
Whole-brain task effects (FWE-corrected at voxel-level, p < .05, k ≥ 3).

Region	Lat.	Peak (MNI)			T_{peak}	P_{voxel}(FWE)	k
		x	y	z			
Orig-Assoc > Com-Assoc							
Lingual G	R	15	−72	−12	6.24	.003	26
Lingual G	L	−9	−78	−5	5.72	.018	4
Bi-Assoc > Com-Assoc							
Lingual G, Hippocampus	R	21	−63	−9	6.52	.001	69
Hippocampus	L	−30	−39	−2	8.34	<.001	18
AG	L	−39	−78	41	6.21	.003	12
Cerebellum	L	−12	−72	−25	6.87	<.001	3
MOG	R	36	−81	28	5.94	.009	3
Bi-Assoc > Orig-Assoc							
IPL (AG, SMG)	R	42	−48	51	6.45	.002	41
IPL (AG, SMG)	L	−39	−51	44	6.08	.005	4
Hippocampus	R	24	−6	−19	5.73	.017	3

Note. AG = Angular Gyrus, SMG = Supramarginal Gyrus, G = Gyrus, MOG = Middle Occipital Gyrus, IPL = Inferior Parietal Lobe.

physical property. This notion is further supported by findings from an fMRI study comparing the generation of metaphors and synonyms, which showed that metaphor generation based on given adjectives (e.g., this room is [dark]: a cave) also involved higher activation of the lingual gyrus besides other regions (Benedek et al., 2014a).

3.2.2.1. Parametric effects of association originality. While Com-Assoc and Orig-Assoc tasks clearly differed in the originality of associations, we still observed considerable variance in the originality of associations within tasks. Hence, as a second approach, we analyzed parametric effects of rated originality across all valid responses in the two single association tasks. This analysis showed that more original association responses were related to higher brain activation in a left-lateralized network of clusters including the inferior frontal gyrus, superior frontal gyrus, superior temporal gyrus and ventromedial prefrontal cortex (vmPFC) as well as in bilateral clusters of the calcarine cortex extending to lingual gyri (see Table 3, and Fig. 3). These additional regions mainly involve frontal regions associated with cued retrieval and response selection and evaluation (Kleinmintz et al., 2018; Thompson-Schill et al., 1997; Vartanian et al., 2018) highlighting the executive nature of goal-directed creative thought processes. The parametric analysis thus indicates the relevance of further brain regions beyond lingual gyri for the generation of original associations, which is likely related to the larger variance of responses across both tasks. In fact, separate parametric analyses per task show that, in the Com-Assoc task, parametric originality effects were most prominent in the IFG and calcarine cortex, whereas in the Orig-Assoc task parametric originality effects were more prominent in the vmPFC and STG (see Supplemental Materials, Tables S4 and S5).

Similar findings have been previously observed in parametric analyses of response creativity in the alternate uses task and in metaphor generation, which implicated the left IFG and the dorsomedial prefrontal cortex for producing more original responses (Benedek et al., 2014a, 2014b). These findings are also partially consistent with those from a similar study asking for verb associations either cued or uncued for creativity (Green et al., 2015), which also found that the generation of original responses involved higher activation of the right lingual gyrus, while effects were strongest in the medial frontal gyrus and the right cerebellum. Moreover, parametric analyses showed that higher originality of verb responses as measured by LSA was associated with higher frontopolar brain activation in a predefined ROI located in left medial PFC, similar to the results of the whole brain analysis in our study, which also implicated the left medial PFC although peaking more ventrally (vmPFC). The vmPFC is recruited during episodic simulation such as in
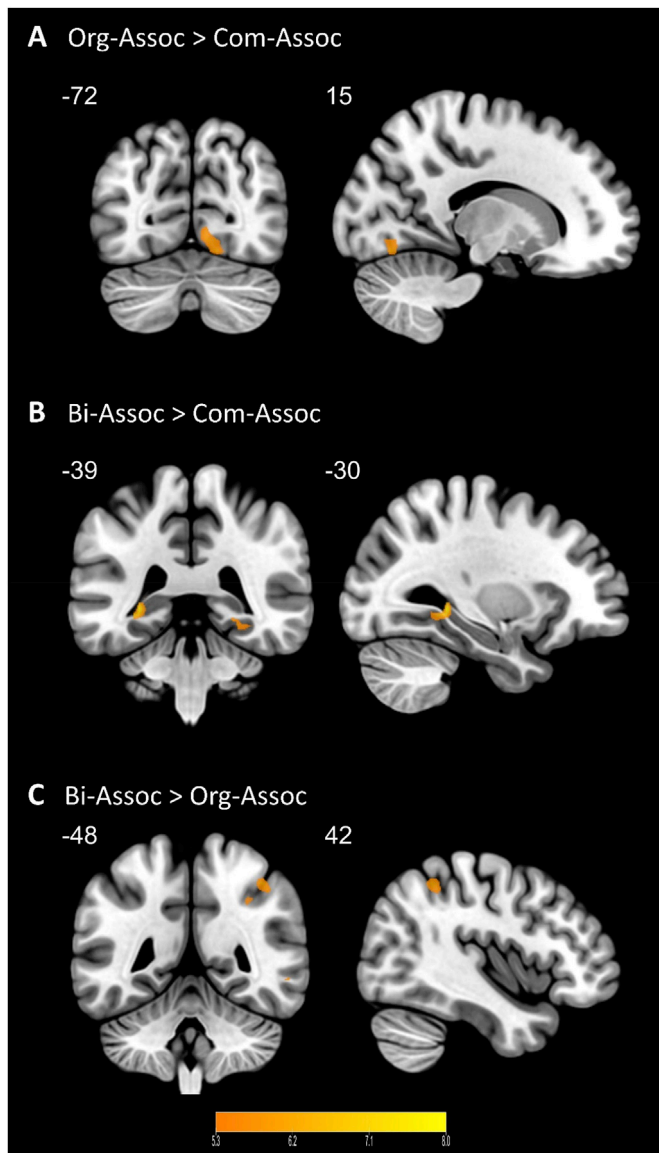
Fig. 2. Whole brain task effects (FWE-corrected at voxel level, p < .05, k≥3). Slice view at x,y,z-coordinates of cluster peaks: A: Org-Assoc > Com-Assoc: Lingual Gyrus (15,-72,-12); B: Bi-Assoc > Com-Assoc: Hippocampus (-30, -39, -2); C: Bi-Assoc > Org-Assoc: IPL (42,-48,51).

Table 3
Parametric analysis for response originality across responses in Com-Assoc and Orig-Assoc tasks (FWE-corrected at voxel-level, p < .05, k ≥ 3).

Region	Lat.	Peak (MNI)			T_{peak}	P_{voxel}(FWE)	k
		x	y	z			
IFG (oper., triang.)	L	−57	21	21	8.66	<.001	147
Calcarine C, Lingual G	R	12	−66	11	6.18	.004	29
Calcarine C	L	−12	−72	14	6.66	.001	21
NC	R	6	6	−2	7.28	<.001	17
STG	L	−60	−3	−9	6.26	.003	12
SMA		−3	15	61	6.93	<.001	10
NC	L	−12	18	4	6.16	.004	7
Cerebellum	R	36	−57	−29	6.01	.007	5
Calcarine C	L	−21	−63	8	5.87	.011	4
NC	L	−6	9	1	5.77	.015	4
vmPFC	L	−6	54	−15	6.18	.004	3

Note. IFG = Inferior frontal gyrus, NC = Nucleus caudatus, STG = Superior temporal gyrus, SMA = Supplemental Motor Area, G = gyrus, C = cortex.
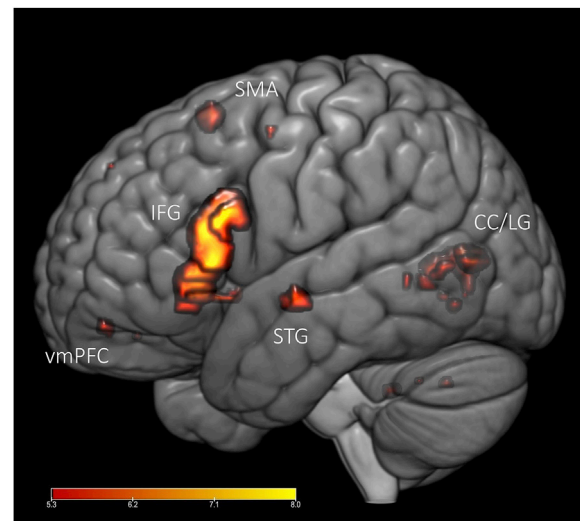

Fig. 3. Whole brain parametric effect of association originality (FWE-corrected at voxel level, p < .05, k≥3).vmPFC = ventromedial prefrontal cortex, IFG = inferior frontal gyrus, STG) superior temporal gyrus, SMA = supplemental motor area, CC = calcarine cortex, LG = lingual gyrus.

reconstruction and imagery of novel scenes (Barry et al., 2019; Hassabis and Maguire, 2007) suggesting that highly original associations responses resulted from strategies based on scene imagery. Together with findings relating medial PFC to semantic distance in analogical mapping (Green et al., 2010), this region seems to play an important in the generation of semantically distant associations.

To further explore the role of visual areas in association generation, we ran a post-hoc parametric analysis including imageability ratings of the adjectives as additional parameter besides response originality (Köper & Schulte im Walde, 2016). This analysis revealed that higher imageability of stimuli resulted in increased brain activation of bilateral inferior parietal cortex (especially angular gyrus and supramarginal gyrus) and right middle and inferior frontal gyrus, whereas lower imageability of stimuli (higher abstraction) involved increased brain activation in visual areas including bilateral lingual gyri and superior occipital gyrus (see Supplemental Material, Table S6). These findings suggest that imageability of stimulus words (which is highly correlated to their concreteness; $r = 0.81$) affects the level of involvement of visual areas in association generation, with more imaginable, concrete words implicating higher involvement of semantic brain regions versus more abstract words implicating higher involvement of visual areas.

3.2.3. Brain activation related to the generation of bi-associations

Contrasts of brain activation during the generation of bi-associations with common associations (Bi-Assoc > Com-Assoc) revealed higher activation in bilateral hippocampus extending to the right lingual gyrus and in the left angular gyrus (see Table 2, and Fig. 2). Similar to the generation of original associations, the generation of bi-associations hence involved higher lingual gyrus activity, but additionally recruited bilateral hippocampus and left angular gyrus. Contrasting the generation of original bi-associations with the generation of original single associations (Bi-Assoc > Orig-Assoc) revealed higher activation in dorsal parts of bilateral inferior parietal lobe involving angular and supramarginal gyrus and in a ventral part of the right hippocampus. These brain structures are considered posterior parts of an episodic simulation network that is involved in reconstructive processes of episodic retrieval but also in constructive processes such as future thinking or divergent thinking (Beaty et al., 2018; Schacter et al., 2012). For example, the generation of novel scenes based on verbal prompts has been related to

hippocampus activity driven by vmPFC (Barry et al., 2019). These findings indicate that the generation of bi-associations involves episodic simulation processes possibly to construct mental scenes that feature both properties.

4. General discussion

Understanding basic elements of creative thinking is an important precondition for the investigation of more complex creative behaviors. Creativity theories posit that creative ideas arise from the retrieval of remote associations that are combined in novel and appropriate way (Mednick, 1962). Therefore, this work devised tasks assessing the generation of original associations and bi-associations, which are thought to represent the abilities to expand and combine concepts, respectively (Abraham et al., 2012; Ward et al., 1997). Two studies examined the cognitive and neural correlates of these association and bi-association processes as elements of creative thought.

Study 1 showed that the generation of original associations and bi-associations (but not the generation of common associations) was correlated with several established indicators of creative potential including divergent thinking ability, broad retrieval ability, openness, and creative behavior. Moreover, study 1 and 2 both found that explicit instructions to find original associations consistently increased response originality, indicating that people can effectively tune response behavior towards creativity (Acar et al., 2020; Said-Metwaly et al., 2020; Weinberger et al., 2016). Together, these findings corroborate the notion that basic association processes capture valid elementary cognitive aspects of creative cognition (Benedek et al., 2012; Merten and Fischer, 1999; Prabhakaran et al., 2014).

At the neural level, the generation of original associations and bi-associations clearly differed from common association generation. The task contrast between original and common associations revealed higher activation in bilateral lingual gyrus, a region implicated in visual encoding and retrieval and in the generation of mental images (Kosslyn et al., 1997; Leshikar et al., 2012; Machielsen et al., 2000). Moreover, the parametric analysis offered a more nuanced result, showing that beyond bilateral activation in lingual and calcarine cortex, more original associations were related to higher brain activation especially in the left IFG. IFG plays a crucial role in cued search and selection of information from semantic memory and was actually found to be prominently involved in all three association tasks. Yet, higher IFG activity was related to more original associations suggesting that higher IFG activity facilitates more effective search and evaluation processes (Kleinmintz et al., 2018) allowing access to more remote locations within the solution space (i.e., semantic network). Activation of lingual gyrus and calcarine gyrus indicated that the generation of original associations to adjectives does not only rely on simple verbal association processes but may additionally imply visually-mediated search strategies.

Additional parametric analyses indicated that the involvement of visual strategies may actually be moderated by the imageability of stimuli. Interestingly, more abstract words prompted higher involvement of visual areas. These findings are consistent with previous research showing that different strategies within the same task imply different brain activation patterns. For example, Leshikar et al. (2012) compared brain activation during encoding of word pairs based on either sentence generation and visual imagery strategies and found higher right lingual gyrus activity related to sentence generation strategy, but also higher right lingual gyrus activity predicting successful recall when employing the visual imagery strategy. Another study showed that right lingual gyrus was more strongly activated when using scene encoding compared to sentence encoding strategies, whereas the left lingual gyrus was more strongly activated during sentence encoding (Johnson and Rugg, 2007). Together, our findings suggest that generating original associations may imply both verbally and visually-mediated retrieval mechanisms. Verbal mechanisms, driven by regions including the left IFG, involve the scanning of semantic memory to retrieve remotely associated concepts. Visual mechanisms, driven by lingual gyri, may additionally imply the generation of mental images in order to cue relevant representations in visual semantic memory. Future research may test the role of verbal versus visual mechanisms in original association generation more directly by means of explicit instructions to use either verbal or visual strategies (Johnson and Rugg, 2007; Leshikar et al., 2012). As an alternative approach, studies may systematically vary the modality of cues (Chrysikou et al., 2016) or the concreteness versus abstractness of cue words (Köper & Schulte im Walde, 2016).

The generation of bi-associations differed from the generation of single associations by stronger activation within hippocampus and inferior parietal lobe (e.g., angular gyrus), which represent hubs of a core network associated with episodic memory and simulation (Schacter et al., 2012). This result suggests that the integration of two unrelated concepts is supported by episodic simulation processes, where the two adjectives trigger the construction of relevant scenes representing these cues. This is a remarkable finding as it shows that bi-association generation does not just represent a more constrained version of association generation, where retrieval considers two cues instead of one, but rather implies qualitatively different cognitive mechanisms to achieve effective conceptual integration. This notion is consistent with previous research showing that the core network of episodic memory and simulation is consistently involved in divergent thinking (Beaty et al., 2018; Madore et al., 2017) and that particularly the left inferior parietal lobe is crucial to the generation of novel ideas (Benedek et al., 2014b; Benedek et al., 2018). These findings help to elucidate the role of episodic simulation in creative cognition by suggesting that they already occur at the level of basic constructive processes, such as the conceptual combination of concepts.

As a potential limitation of this study, the Bi-Assoc and Org-Assoc tasks differed in how explicitly they instructed to be creative. We assume that the generation of valid, balanced bi-associations also involves remote association processes because common associations for one stimulus typically would not be reasonably related to the other. Hence, Bi-Assoc and Org-Assoc both require remote associations while Bi-Assoc performance involves higher conceptual integration demands. Future research could examine the role of originality in bi-association generation more directly, by instructing participants explicitly about the need to be creative and analyzing differences in originality across responses. Moreover, stimuli could be pre-selected specifically in terms of their semantic distance, imageability versus abstractness and maybe other features in order to be able to study their effect on strategies and brain process in the association process.

Together, these findings offer new insights in the brain mechanisms underlying the generation of remote associations and conceptual integration, two key processes of creative thinking. Importantly, they advise caution when attributing cognitive tasks to specific modalities such as verbal or visual (Benedek et al., 2019). While the association tasks of this study involved verbal stimuli (one or two adjective words), the brain activation findings indicate that generating original associations and bi-association for characteristics recruits structures related to the generation of mental images and scenes, thus suggesting the relevance of visually-mediated search strategies. These findings extend our understanding of the role of basic memory processes in creative cognition (Benedek and Fink, 2019). Hence, considering evidence from neuroscience can help us to revise overly simplistic cognitive models of creativity, and the investigation of elementary cognitive processes in creative thought is viewed a particularly useful approach to this end.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2020.116586.

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