



Research report

To create or to recall original ideas: Brain processes associated with the imagination of novel object uses

Mathias Benedek^{a,b,*}, Till Schües^{a,b}, Roger E. Beaty^c, Emanuel Jauk^{a,b}, Karl Koschutnig^{a,b}, Andreas Fink^{a,b} and Aljoscha C. Neubauer^{a,b}

^a Institute of Psychology, University of Graz, Austria

^b BioTecMed Graz, Austria

^c Department of Psychology and Center for Brain Science, Harvard University, USA

ARTICLE INFO

Article history:

Received 3 May 2017

Reviewed 14 August 2017

Revised 11 September 2017

Accepted 30 October 2017

Action editor Pia Rotshtein

Published online 11 November 2017

Keywords:

fMRI

Creativity

Memory

SMG

Inferior parietal cortex

Medial temporal lobe

ABSTRACT

This fMRI study investigated what brain processes contribute to the generation of new ideas. Brain activation was measured while participants generated new original object uses, recalled original object uses, or recalled common object uses. Post-scan evaluations were used to confirm what ideas were newly generated on the spot or actually retrieved from memory. When compared to the recall of common ideas, the generation of new and old original ideas showed a similar activation pattern including activation of bilateral parahippocampal and mPFC regions, suggesting that the construction of new ideas builds on similar processes like the reconstruction of original ideas from episodic memory. As a difference, the generation of new object uses involved higher activation of a focused cluster in the left supramarginal gyrus compared to the recall of original ideas. This finding adds to the converging evidence that the left supramarginal gyrus is crucially involved in the construction of novel representations, potentially by integrating memory content in new ways and supporting executively demanding mental simulations. This study deepens our understanding of how creative thought builds on and goes beyond memory.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

One particularly remarkable capacity of our brain is the ability to create new mental representations that clearly go beyond what was previously stored in memory. This imaginative capacity is the foundation of important cognitive activities such as planning, future thinking and creative idea generation (Abraham, 2016). Interestingly, the generation of novel

representations often implicates similar brain structures as the recall from memory (Schacter, Addis, & Buckner, 2007), but little is known about what brain processes are specific to creating new ideas. Recent research employing the alternate uses task suggested that brain activation in the left anterior inferior parietal cortex dissociates between the generation of newly generated and recalled objects uses (Benedek et al., 2014b), but in this study, it remained unclear whether

* Corresponding author. Institute of Psychology, University of Graz, Universitätsplatz 2, 8010 Graz, Austria.

E-mail address: mathias.benedek@uni-graz.at (M. Benedek).

<https://doi.org/10.1016/j.cortex.2017.10.024>

0010-9452/© 2017 Elsevier Ltd. All rights reserved.

recalled uses represented common uses that are likely retrieved from semantic memory or known original uses that are likely retrieved from episodic memory. Therefore, this study aimed to replicate and extend previous findings by investigating the specific brain activation associated with the generation of new original uses, the recall of original uses, and the recall of common uses.

1.1. The role of memory in idea generation

Theoretical accounts of idea generation have long assumed that new ideas do not develop *ex nihilo* but rely on meaningful variations or recombinations of available knowledge (Koestler, 1964, p. 751; Stein, 1953). Highly creative ideas are thought to represent a fruitful integration of particularly unrelated concepts (Mednick, 1962). These notions have been supported by behavioral research showing that various associative processes play an important role for creative idea generation (*viz.* divergent thinking; Benedek, Könen, & Neubauer, 2012; Silvia, Beaty, & Nusbaum, 2013), and that divergent thinking relies on semantic memory (Abraham & Bubic, 2015; Leon, Altmann, Abrams, Gonzalez Rothi, & Heilman, 2014) as well as episodic memory (Addis, Pan, Musicaro, & Schacter, 2016; Madore, Addis, & Schacter, 2015). But memory retrieval alone, of course, cannot lead to new ideas. The generation of new ideas is assumed to further rely on executive processes that act upon available knowledge (Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Benedek, Mühlmann, Jauk, & Neubauer, 2013; Chen et al., *in press*). These executive processes guide the strategic search, selection and integration of relevant knowledge and are needed to guide mental simulations and evaluate outcomes (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014c, 2017; Silvia, 2015). Taken together, associative and executive processes can be assumed to interact in the forging of novel ideas.

Cognitive neuroscience has previously revealed important insights in the brain processes supporting the generation of novel representations and ideas. For example, research on future thought has compiled extensive evidence that thinking about the future shares many brain regions with the recall from episodic memory (Addis et al., 2007; Hassabis & Maguire, 2007; Szpunar, 2010). These common brain structures include medial prefrontal cortex, medial temporal lobe and lateral parietal cortex (Schacter et al., 2007), which further overlap with structures of the default mode network (Spreng, Mar, & Kim, 2009). This core network is engaged in constructive mental simulations based on episodic memory (*i.e.*, episodic simulations), which are relevant for both the reconstruction of scenes during episodic recall and the imagination of novel events (Schacter et al., 2012). This network is also commonly implicated in other cognitive activities involving imagination such as mental navigation and theory of mind (Spreng et al., 2009). These findings provide compelling neuroscientific evidence for the crucial role of memory for constructing novel representations.

Brain research on creative cognition has shown that engaging in creative idea generation implicates a similar left-lateralized brain network including the inferior parietal lobe, prefrontal cortex, and in the posterior cingulate (Abraham et al., 2012; Beaty, Christensen, Benedek, Silvia, & Schacter,

2017; Bendetowicz, Urbanski, Aichelburg, Levy, & Volle, 2017; Benedek et al., 2014a, 2016; Fink et al., 2009; for a review, see Gonen-Yaacovi et al., 2013). These brain regions can be mostly attributed to the default mode network and the executive control network, which have often shown to anti-correlate in previous research (Fox et al., 2005). Interestingly, analyses of the functional brain connectivity actually revealed increased coupling between default and executive network regions during many forms of creative cognition including divergent thinking (Beaty, Benedek, Kaufman, & Silvia, 2015), poetry composition (Liu et al., 2015), metaphor production (Beaty, Christensen, et al., 2017), and musical improvisation (Pinho et al., 2016). These findings provide neuroscientific evidence suggesting that generative and evaluative processes cooperate during creative thought (Beaty, Benedek, Silvia, & Schacter, 2016; Chrysikou, Weber, & Thompson-Schill, 2014; Jung, Mead, Carrasco, & Flores, 2013; Zabelina & Andrews-Hanna, 2016).

1.2. Creating new ideas

Behavioral and neuroscientific research provide converging evidence for the crucial role of memory processes for creative thought. But what brain processes are specific to the generation of a genuinely novel representation? A number of fMRI studies on creative cognition have contrasted the generation of creative and common object uses (Chrysikou & Thompson-Schill, 2011; Fink et al., 2014). In this research, an idea is viewed as creative when it is both original and useful (Diedrich, Benedek, Jauk, & Neubauer, 2015; Runco & Jaeger, 2012; Stein, 1953; sometimes “surprising” is added as a third criterion of creativity, *cf.*; Simonton, 2012). However, analyses of the response behavior during idea generation revealed that original ideas are not always newly created on the spot but sometimes recalled from memory (Gilhooly, Fioratou, Anthony, & Wynn, 2007). A recent fMRI study capitalized on this issue to discriminate brain activation associated between new and recalled ideas. It assessed brain activation during self-paced idea generation, and after the scanner session asked participants to identify all ideas as either being recalled from memory or newly generated (Benedek et al., 2014b). Behavioral analyses showed that people in fact tend to start by recalling uses from memory before shifting toward the generation of novel uses. Importantly, the generation of new ideas was associated with increased brain activation in the left anterior supramarginal gyrus (SMG).

This previous study suggests that the left SMG is important for the generation of new ideas, but it also raised new questions. Recalled uses can vary substantially in their originality, ranging from prototypical uses (*e.g.*, use a hat as head covering) to more original uses that people have been occasionally witnessed in the past (*e.g.*, use a hat to collect donations, or as a Frisbee). Critically, these recalled ideas may differ in the type of memory they were drawn from: highly common, prototypical ideas are likely recalled from semantic memory, whereas previously experienced original object uses are more likely obtained from searches of episodic memory, which contains autobiographic details on where and how this unusual object use was encountered (Addis et al., 2016; Gilhooly et al., 2007). In the present study, we aimed to

address this issue by distinguishing three well-defined conditions in the alternate uses task: a) the generation of new uses, b) the recall of original uses, and c) the recall common uses. Contrasting the brain activation between the generation of new original uses and the recall of known original ideas should be sensitive to brain processes involved in the generation of truly novel representations. Following previous research, we assumed that the generation of new ideas is associated with increased SMG activation (Benedek et al., 2014b; Fink et al., 2010). Moreover, the generation of new ideas and the recall of original ideas are both assumed to rely on constructive processes associated with episodic simulation compared to the recall of common ideas, and, therefore, are expected to invoke brain structures associated with episodic memory retrieval (e.g., medial temporal lobe, inferior parietal cortex, and medial prefrontal cortex; Benoit & Schacter, 2015; Wagner, Shannon, Kahn, & Buckner, 2005).

2. Material and methods

2.1. Participants

The final sample consisted of 42 healthy adults (17 male), mostly university students, with a mean age of 24.31 years ($SD = 4.3$; range = 19 to 36). All participants were native German speakers, right-handed, had normal or corrected-to-normal vision, and no self-reported history of CNS-affecting drugs, mental or neurological diseases. Two additional participants were not included in the final sample, one who aborted the scanning session, and one who had trouble with the provided vision correction. Participants were recruited by local advertisements and gave written informed consent. They were either paid or participated for partial course credit. The study was approved by the ethics committee of the local university.

2.2. Experimental task and procedure

The alternate uses task (AUT) requires generating uses for common objects (e.g., a hat) and is a classic assessment of

domain-general creative cognition (Kaufman, Plucker, & Baer, 2008). Here, we modified the task by employing three different experimental conditions during fMRI assessment: In the *Create Original* condition, participants were asked to think of novel uses for the object that they have never seen or heard of before (e.g., “use hat as lamp shade”). In the *Recall Original* condition, they were asked to recall a non-typical, original use of the object that they have previously encountered (e.g., “use hat to collect donations”). Finally, in the *Recall Common* condition, participants were asked to recall the most common use of the object (e.g., “use hat to cover one’s head”). This design builds on previous research on spontaneous idea generation (Benedek et al., 2014b) and extends it in two important ways: First, by discriminating between the recall of original and common uses, which leads to a subtler contrast between the creation and recall of original ideas. Second, participants are directed to engage in specific modes of thought, which ensures a balanced amount of well-defined generation periods compared to spontaneous idea generation.

In each trial, the name of the target-object was presented in white letters on black background. In the *Create Original* and *Recall Original* conditions, participants had 15 sec to create or recall one original use for this object, respectively. In the *Recall Common* condition, participants had only 4 sec to recall the most common use of this object, which was found enough time for recalling typical uses according to pilot tests. After this *idea generation* period, the object word appeared in green letters for 4 sec (*response period*), prompting the participants to vocalize their response (cf. Benedek et al., 2014a; Fink et al., 2009). Participants were instructed to speak only in this response period. If they had ideas earlier within the 15s-generation period, they were asked to continue thinking of even more original object uses until the onset of the response period. Fig. 1 illustrates the procedure of the scanner task.

Participants performed a total of 60 trials including 15 *Create Original*, 15 *Recall Original*, and 30 shorter *Recall Common* trials. Trials were grouped in blocks of five trials per condition to avoid permanent task-set switching efforts. Each task block was preceded by a task cue (5 sec) indicating the task condition in this block (“Create: Original”; “Recall: Original”; or “Recall: Common”). Trials within blocks were separated by a

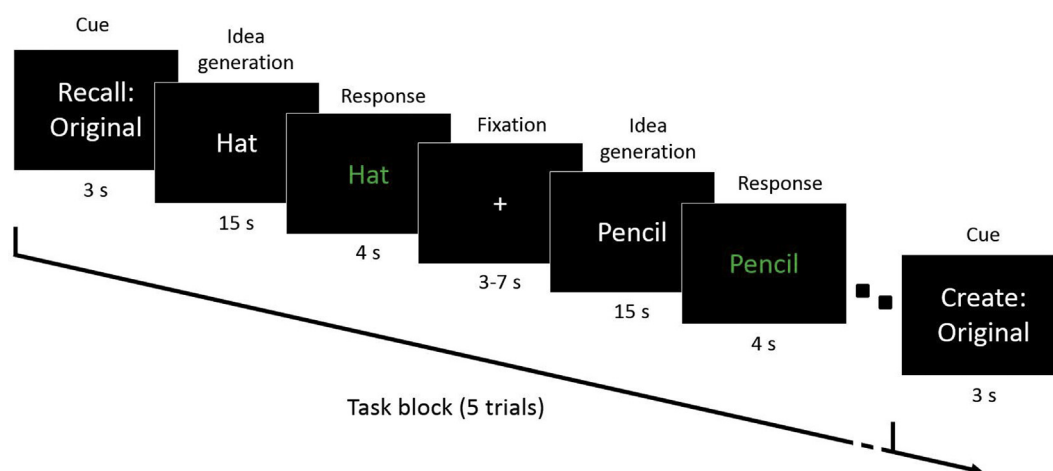


Fig. 1 – Procedure of scanner task.

jittered fixation period of 3–7 sec following each response period. *Create Original* and *Recall Original* blocks alternated with *Recall Common* blocks. We used a set of 30 objects as stimuli (cf. Fink et al., 2009), half of which were used in either the *Create Original* or the *Recall Original* tasks; all stimuli were also used in the *Recall Common* tasks as the brief recall of common object uses should not interfere with the generation or recall of original uses. We kept the sequence of objects fixed for all participants, but varied the sequence of task blocks between participants to ensure that the assignment of objects to the *Create Original/Recall Original* conditions was counterbalanced across participants. At the beginning and end of the session we presented a fixation cross for 10 sec. The total scanner task took about 20 min.

Before the scanner session, participants were instructed about the upcoming tasks in two ways. They performed two alternate uses task (2 min, self-paced) and afterward were shown their ideas and asked to classify them as either newly generated or retrieved from memory. This procedure was intended to sensitize them for the difference between new and old ideas during idea generation. They then received thorough instructions about the three experimental conditions and performed a total of eight exercise tasks for different conditions.

In the scanner, a T1-scan was performed, followed by the acquisition of functional MRI data during task performance. During task performance, all verbal responses were recorded and immediately transcribed by the experimenter. In a post-scan evaluation, the participants were presented a list of their responses next to each object but without mentioning the assigned task conditions, and they were asked to indicate for each response whether it had been newly created or recalled from memory during the scanner task (Benedek et al., 2014b; Silvia, Nusbaum, and Beaty, in press). This rating allows capturing responses that were not consistent with instructed task conditions and was used for response-based analyses. All responses were additionally evaluated for creativity by two independent judges on a four-point rating scale ranging from 0 (uncreative) to 3 (highly creative) following standard rating procedures (Benedek et al., 2013; Silvia, 2011). Inter-rater reliability was high, ranging from ICC = .83 to .95 across tasks (i.e., objects). Creativity ratings were averaged across raters.

2.3. 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. We acquired T1-weighted 3D-MPRAGE structural images (TR = 1560 msec, TE = 2.07 msec, flip angle = 9°, 176 sagittal slices, 1 × 1 × 1 mm, FoV = 256 × 256 mm, TI = 900 msec). BOLD-sensitive T2*-weighted functional images were acquired using a single shot gradient-echo EPI pulse sequence (TR = 2400 msec, TE = 30 msec, flip angle = 90°, 39 axial slices, 3 × 3 × 3 mm, distance factor 20%, FoV = 240 × 240 mm, interleaved slice ordering) and online motion-corrected. The first two volumes were discarded to allow for T1 equilibration effects. Head motion was restricted using firm padding that surrounded the head.

Visual stimuli were presented using the software Presentation (Neurobehavioral Systems, Albany, CA), projected onto a screen, and viewed through a mirror attached to the head coil. Verbal responses were recorded by means of a MRI-compatible noise canceling microphone (FOMRI-III; Optoacoustics, Mazor, Israel) also attached to the head coil.

2.4. fMRI data analysis

Functional MRI data were preprocessed and analyzed using SPM 12 (Wellcome Department of Imaging Neuroscience, London, UK). Preprocessing steps included slice time acquisition correction (referenced to midpoint of slice number), motion correction (interpolation with 4th-degree B-spline), spatial normalization into MNI space by means of the deformation field of coregistered, segmented structural data, and smoothing with a 6-mm full-width at half-maximum Gaussian kernel.

Effects were estimated using the General Linear Model (GLM) as implemented in SPM 12. At the first level, we included the idea generation periods of the three experimental conditions (*Create Original*, *Recall Original*, and *Recall Common*), which were modeled with boxcar functions convolved with the canonical hemodynamic response function (HRF). Additionally, six motion parameters were entered as regressors of no interest. Linear contrasts were used to obtain subject-specific estimates, which were entered into a second-level analysis treating subjects as a random effect.

Two different analysis strategies were realized: In the *task-based* analysis, the experimental conditions were defined according to the instructed task conditions. It assumes that participants were generally engaged in the instructed thinking process, even if they eventually came up with no or no task-conform response in some trials. In this analysis, all trials from all participants were maintained. In an additional *response-based* analysis, experimental conditions were defined according to the post-scan evaluations. In this analysis, the *Create Original* condition encompassed all trials where participants had effectively generated novel uses, and the *Recall Original* condition encompassed all trials where participants had recalled original uses (independent of actual task instructions). Moreover, we included only participants who succeeded to generate at least 10 valid responses for each condition, which led to the exclusion of four participants (remaining sample $n = 38$). For reasons of clarity, and because the analyses are not independent, we decided to focus on the potentially more rigorous response-based analysis in the presentation of findings, but additionally provide all findings from task-based analyses in the supplemental materials for comparison. Both analysis strategies led to largely the same results, but the task-based analysis involved some additional clusters especially in the *Create Original* > *Recall Original* contrast (see [Supplemental Material](#)). These additional activations may in part be due to higher test power when retaining more participants but may also be related to the less rigorous selection of trials in the task-based analysis.

Additional whole-brain analyses contrasted the brain activation during the generation of new and recalled original object uses with the recall of common uses. Since the generation period for *Recall Common* tasks was only 4 sec, we limited

the *Create Original* and *Recall Original* tasks to the first 4 sec of idea generation in all analyses involving the *Recall Common* condition to ensure that contrasts rely on similar time frames.

Findings of the whole-brain analyses are reported when they are significant at cluster-level ($p < .01$, FWE-corrected) using a cluster-forming threshold of $p < .001$ (uncorrected). Finally, intrinsic functional connectivity networks were identified using a group-based independent component analysis as implemented in CONN (v16; Whitfield-Gabrieli & Nieto-Castanon, 2012) to examine the brain network affiliation of significant clusters. Pre-processed functional images were entered into a principal component analysis (PCA) and we reduced the data to 20 components using the Infomax algorithm, and applied a back-reconstruction procedure via the GICA1 algorithm (Erhardt et al., 2011) using the individual time courses and spatial maps.

3. Results

3.1. Behavioral analysis

Participants responded valid object uses in 94% of the *Create Original* tasks, 97% of the *Recall Original* tasks and 100% of the *Recall Common* tasks. According to the post-scan evaluations, participants were able to create new uses in 72% of the *Create Original* tasks, while 22% were identified as recalled. In the *Recall Original* tasks, participants successfully recalled original uses in 84% of cases, while 13% were later identified as actually being novel. Responses to the 30 *Recall Common* tasks were always identified as known, highly common object uses. This resulted in an average total of 13 *new original ideas* ($SD = 1.6$), and 16 *recalled original ideas* ($SD = 2.1$), and 30 ($SD = 0$) recalled common responses.

The three types of ideas differed in their rated creativity ($F[1.53, 56.34] = 1334.74$, $p < .001$; $\eta^2 = .97$). Bonferroni post-hoc analyses indicated that novel object uses were judged as more creative than recalled original uses ($p < .001$), and new and recalled original uses both were judged much more creative as common uses ($p < .001$; see Fig. 2).

3.2. fMRI analysis

3.2.1. Creating versus recalling original ideas

A whole-brain response-based analysis (classification based on post-scan evaluations) contrasting the brain activation between *Create Original* and *Recall Original* conditions revealed one significant cluster. The generation of novel ideas was associated with increased brain activation in the left anterior inferior parietal cortex (aIPL; BA 40) representing the SMG and of parts of the postcentral gyrus (see Table 1 and Fig. 3). The inverse contrast did not reveal a significant effect. Mapping the significant cluster peak on the intrinsic functional connectivity networks of our data, it was most reliably represented in a network showing connections between bilateral SMG, prefrontal regions and inferior temporal gyrus lateralized to the left hemisphere. This connectivity pattern suggests that the observed left SMG cluster is part of the frontoparietal control network (FPCN; Yeo et al., 2011).

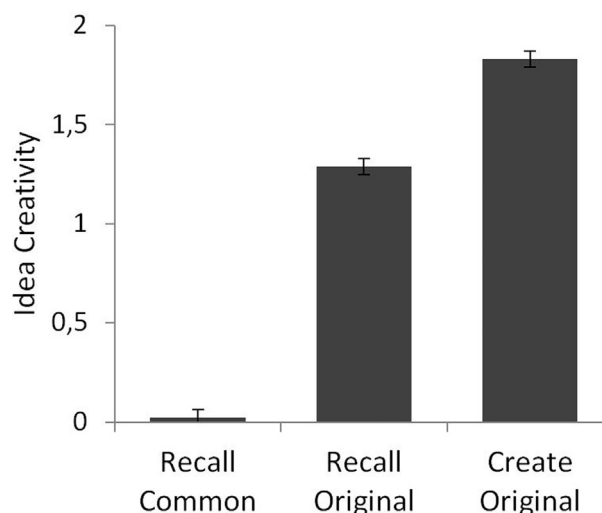


Fig. 2 – Rated creativity of object uses when producing common uses (*Recall Common*), recalling original uses (*Recall Original*), and creating new uses (*Create Original*).

Table 1 – Contrasts of brain activation between different modes of idea generation: creation of new, original object uses (*Create Original*), recall of original object uses (*Recall Original*), and recall of common object uses (*Recall Common*). FWE-corrected at cluster-level ($p < .01$), with cluster-forming threshold $p < .001$ (uncorrected).

Region	Lat.	Peak (MNI)			T_{peak}	k	p_{clust} (FWE)
		x	y	z			
<i>Create Original > Recall Original</i> ^a							
aIPL (SMG, PCG)	L	-33	-40	47	4.91	320	<.001
<i>Create Original > Recall Common</i> ^b							
mPFC		3	41	-10	7.26	292	<.001
PHC, Hipp, Fusiform G	L	-30	-40	-7	6.37	249	<.001
IPL (SMG, PCG)	L	-54	-25	41	6.35	211	<.001
Cuneus, Precuneus	L	-12	-58	23	5.85	146	<.001
PHC, Hipp	R	24	-34	-13	7.50	140	<.001
AG, MOG	L	-39	-79	32	6.73	105	.002
<i>Recall Original > Recall Common</i> ^b							
PHC, Hipp, Fusiform G	L	-30	-34	-16	6.55	221	<.001
mPFC		3	38	-13	6.44	199	<.001
Cuneus, Precuneus	L	-12	-52	11	6.41	183	<.001
PHC, Hipp, Fusiform G	R	24	-34	-13	6.61	173	<.001
AG, MOG	L	-36	-79	35	6.22	142	<.001
AG, MOG	R	45	-67	29	5.61	123	.001

Notes. MNI coordinates. Lat. = Laterality, k = cluster size, L/R = Left/right; AG = Angular Gyrus, aIPL = anterior Inferior Parietal Lobe, G = Gyrus, Hipp = Hippocampus, MOG = Middle Occipital Gyrus, mPFC = Medial Prefrontal Cortex, PCG = Postcentral Gyrus, PHC = Parahippocampal Cortex, SMG = Supramarginal Gyrus.

^a The inverse contrast (*Create Original < Recall Original*) did not yield any significant effect.

^b This analysis focuses on the first 4 sec of idea generation.

3.2.2. Producing original versus common ideas

Additional whole-brain analyses contrasted the brain activation during the generation of new and recalled original object uses with the recall of common uses (with all trials limited to

Create Original > Recall Original

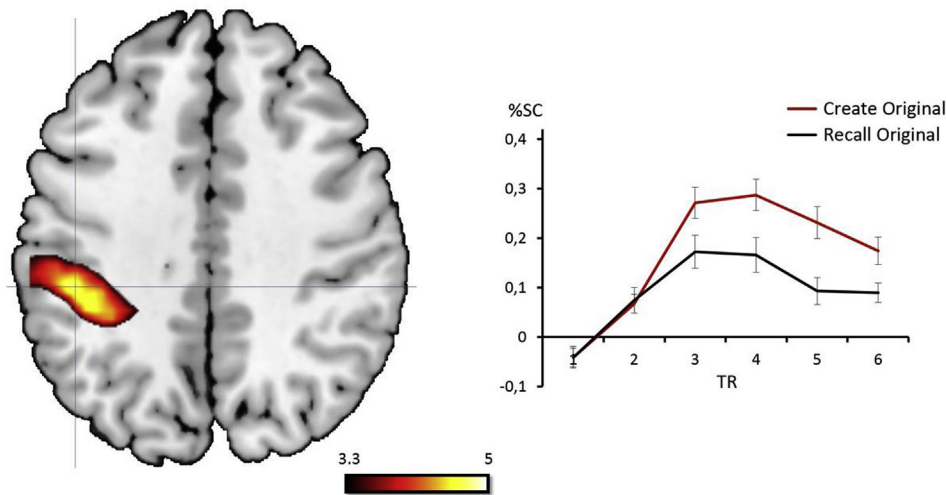


Fig. 3 – A whole brain analysis (T-map) of the contrast *Create Original > Recall Original* yielded one significant cluster ($p < .01$, FWE at cluster-level) in the left anterior inferior parietal cortex (supramarginal gyrus, and postcentral gyrus). This cluster is depicted in the axial slice at $x = -45$, together with its signal change (%SC) plotted over time (TR 1 to TR 6 corresponding to 2.4 to 14.4 sec, respectively).

the first 4 sec of idea generation, since the Recall Common trials were only 4 sec). The contrast *Create Original > Recall Common* showed that the generation of novel object uses was associated with higher brain activation than the recall of common uses in six compact clusters including the left anterior IPL (SMG), medial prefrontal cortex (mPFC), bilateral parahippocampal cortex, and ventral and posterior parts of the left IPL including the left angular gyrus (see Table 1). Similarly, the contrast *Recall Original > Recall Common* revealed that the recall of original object uses was associated with higher brain activation than the recall of common uses in mPFC, bilateral parahippocampal cortex and bilateral angular gyrus, but notably not the left anterior IPL/SMG (see Table 1).

As a control analysis, we checked how the main contrast (*Create Original > Recall Original*) would be affected when focusing on the first 4 sec of idea generation. In this truncated analysis, the left IPL effect is still observed and yields essentially the same single cluster [peak MNI (x,y,z): $-33, -34, 47$; $T = 4.65$; $k = 51$, $p < .001$].

3.2.3. Parametric analysis for idea creativity

We conducted a parametric analysis for idea creativity to explore what brain region is sensitive to the creativity of ideas. This analysis considered all trials from the Create Original and Recall Original tasks (trials from the Recall Common condition were not included, because this condition showed no reasonable variation in rated creativity and generation periods were shorter). A whole-brain analysis revealed no effect of idea creativity at FWE cluster-level. For a more liberal criterion (peak-level $p < .001$, uncorrected, $k \geq 10$), we observed that idea creativity was associated with higher brain activation in a cluster in the left SMG [peak voxel MNI (x,y,z): $-48, -34, 38$; $k = 20$; $T = 3.73$]. This cluster overlaps with the IPL cluster observed in the main contrast of Create Original and Recall Original conditions.

4. Discussion

This study aimed to identify the brain processes involved in the generation of genuinely new ideas. Previous research suggests that the generation of newly generated versus recalled object uses is associated with increased activation in the left anterior IPL, particularly the left supramarginal gyrus (SMG; Benedek et al., 2014b). This previous study used a self-paced idea generation design, which implied high ecological validity but also low control on the quantity and timing of response behavior. Moreover, it did not distinguish between recalled original or common ideas, which might be related to different components of memory. Therefore, the present study aimed to replicate and extend findings in a more controlled experimental design, explicitly asking participants to either create new object uses, recall original uses, or name typical object uses. To enable response-based analyses, all ideas were reviewed and classified by the participants, and evaluated by independent judges.

The response-based analysis showed that creating new ideas was associated with increased left SMG (anterior IPL) activation compared to the generation of known but still original ideas. The observed cluster overlaps with the SMG regions found in previous study comparing the spontaneous generation of new versus recalled uses (Benedek et al., 2014b), thereby providing a clear replication of this new/old idea effect. Notably, this effect is highly focused: The SMG cluster was the only significant effect in whole-brain analyses of this as well as the previous study. Further evidence comes from a whole-brain parametric analysis showing that brain activation in the left SMG increased as a function of idea creativity. While this parametric analysis provides another perspective on the data, it is not fully independent from the task contrasts, because ideas in Create Original were more creative than

those in the Recall Original condition. Finally, the left SMG/aIPL region was also observed when contrasting brain activation during the generation of new original ideas but not recalled original ideas with recalled common ideas. Together these findings add to the mounting evidence relating the SMG in the left anterior IPL with the generation of novel ideas. The left SMG has been consistently implicated when comparing the generation of creative versus common object uses (Fink et al., 2014, 2010; Kleibeuker, Koolschijn, Jolles, De Dreu, & Crone, 2013). Moreover, it showed increased activation following a three-week creativity training (Fink et al., 2015). Taken together, there is converging evidence that the generation of novel ideas involves focused and robust activation in the left SMG.

What is the functional role of the left SMG in creating novel object uses? The SMG is situated just posterior of modal somatosensory association areas and has been implicated as a supramodal convergence zone (Binder, Desai, Graves, & Conant, 2009; Binder & Desai, 2011). High-level integration of multimodal information should be very relevant for assessing novel ways to make use of specific object properties. The ventral inferior parietal lobe has also been proposed to serve as an episodic buffer, where retrieved episodic information is integrated into a unitary episodic representation (Vilberg & Rugg, 2008), thereby linking the central executive with episodic memory (Baddeley, 2000). This view is consistent with viewing the SMG as a parietal hub in the frontoparietal control network (Yeo et al., 2011). It may be involved in executive processes acting upon memory during particularly demanding episodic simulations during the generation of potential new ideas for object uses (cf. Spreng et al., 2014). Especially anterior parts of the left SMG have also been implicated in the cross-modal processing of object features (Grefkes, Weiss, Zilles, & Fink, 2002) and the representation of action (Binder & Desai, 2011; Tunik, Rice, Hamilton, & Grafton, 2007). Moreover, the closely adjacent left postcentral gyrus and anterior intraparietal sulcus are involved in keeping object features in working memory (Takahama, Miyauchi, & Saiki, 2010) and perform visuomotor transformations during tool grasping (Stark & Zohary, 2008). Since part of this evidence is concerned with object-related processing, it opens up the question to what extent the left SMG activation might be specific to the generation of novel ideas in the context of objects. This question should be addressed in future research examining common and distinct brain activations when generating novel ideas in different modalities (e.g., creating object uses vs creating musical or verbal ideas).

Another interesting observation is the clear hemispheric lateralization of the SMG. Virtually all of the reported findings on creating novel object uses exclusively concerned the left SMG. This observation is in line with the notion that verbal, memory-related processes are generally found to be left-lateralized (Binder et al., 2009; Binder & Desai, 2011), whereas the right inferior parietal cortex has rather been linked to attention-related processes (Sarter, Givens, & Bruno, 2001). For example, a recent study found that self-generated thought during different divergent thinking tasks invoked a left-lateralized network of frontal and parietal brain regions, but experimentally-induced focused internal attention during these tasks was related to increased activation of the right

SMG (Benedek et al., 2016). The right SMG also showed increased functional connectivity with the visual network, which decreased activation during internal attention, suggesting that the right SMG is involved in top-down suppression of irrelevant sensory information processing.

The present study was particularly concerned with the role of memory for idea generation. Previous research on creative idea generation partly disregarded that an original idea is not necessarily new and that recalled ideas may still differ in their originality (Gilhooly et al., 2007). For example, while a previous study distinguished between new and old ideas (Benedek et al., 2014b), it still is possible that recalled ideas comprised both known original uses and known highly common uses. New original uses were judged more creative than recalled original uses, and recalled original uses were more creative than common uses, which underscores the relevance to discriminate between these three conditions. Considering these different types of idea generation, the SMG effect can now be more clearly pinned down to the process of creating novel representations rather than to potentially higher accessibility of common uses.

As another finding, the recall of original uses involved higher bilateral activation of (para)hippocampal regions, angular gyrus, and medial prefrontal cortex (mPFC) compared to the recall of common object uses. These structures are commonly associated with episodic memory retrieval (Benoit & Schacter, 2015; Hassabis & Maguire, 2007), which supports the assumption that known original uses are recalled from episodic memory and linked to specific scenes where these original uses were encountered. Critically, the generation of new ideas also involved higher bilateral parahippocampal activation, left angular gyrus, and mPFC compared to the recall of common uses. This overlap supports the notion that creative idea generation involves similar constructive processes as during episodic recall (Addis et al., 2016; Madore et al., 2015). Retrieving episodic memories requires the mental reconstruction of complex scenes, which are relevant for episodic recall but also for thinking about possible future events (Hassabis & Maguire, 2007; Schacter, Addis, & Buckner, 2007). The present findings suggest that, just as future thought, creative idea generation may also rely on episodic simulations supported by parahippocampal and mPFC structures (Mullally & Maguire, 2014; Schacter et al., 2012). When imagining new object uses, these mental simulations could serve to undertake complex simulations facilitating the exploration of potential object uses in the mind's eye. The additional activations of the left SMG, as part of the frontoparietal control network, may further indicate that the generation of novel object uses involves more controlled, action-related simulations of new ways to handle or arrange objects than the recall of previously seen original uses. The assumption that creative idea generation implies higher executive demands than episodic recall is also in line with research highlighting the importance of executive control in creative thought (Beatty, Christensen, et al., 2017; Benedek et al., 2014c).

As a limitation of this study, the Recall Common tasks were considerably shorter than the Recall Original/Create Original tasks (i.e., 4 sec vs 15 sec), which may affect the magnitude of the observed BOLD response (e.g., Dale & Buckner, 1997) and eventually the reliability of the results. Since the recall of

common object uses is typically much faster than the recall or generation of original uses, we could not fully avoid a difference in task duration. We aimed to counteract this issue by using twice as many *Recall Common* tasks and by limiting *Recall Original/Generate Original* tasks to the first 4 sec of idea generation in all contrasts involving the *Recall Common* condition. While these adaptations are suited to make conditions more comparable, they may imply yet other confounds such as that the *Recall Common* condition included more objects.¹ Therefore, findings for these contrasts should be interpreted with caution. Notably, these limitations only affect the complementary analyses involving the recall of common uses, but not the main contrast between the recall and generation of original ideas.

To sum up, the generation of new and recalled original object uses involves common as well as distinct brain processes. They share a bilateral activation of the parahippocampal cortex and of the mPFC, which may reflect memory-related processes supporting episodic simulations that are equally relevant for the reconstruction of previously encoded mental scenes as well as for the construction of novel mental scenarios (Mullally & Maguire, 2014; Schacter et al., 2012). As a discriminant characteristic, however, generating new ideas involves stronger activation of the left SMG. Constructing novel ideas hence may imply higher demands on multimodal integration controlled mental simulation based on memory content, supporting the creative act of going beyond the known and creating something new.

Acknowledgments

This research was supported by a grant from the Austrian Science Fund (FWF): P29801. The authors are grateful to Jürgen Pretsch and Thomas Zussner for their help in this study.

Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.cortex.2017.10.024>.

REFERENCES

- Abraham, A. (2016). The imaginative mind. *Human Brain Mapping*, 37, 4197–4211.
- Abraham, A., & Bubic, A. (2015). Semantic memory as the root of imagination. *Frontiers in Psychology*, 6, 325.
- Abraham, A., Pieritz, K., Thybush, K., Rutter, B., Kröger, S., Schweckendiek, J., et al. (2012). Creativity and the brain: Uncovering the neural signature of conceptual expansion. *Neuropsychologia*, 50, 1906–1917.
- Addis, D. R., Pan, L., Musicaro, R., & Schacter, D. L. (2016). Divergent thinking and constructing episodic simulations. *Memory*, 24, 89–97.
- Addis, D. R., Wong, A. T., & Schacter, D. L. (2007). Remembering the past and imagining the future: common and distinct neural substrates during event construction and elaboration. *Neuropsychologia*, 45, 1363–1377.
- Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, 4, 417–423.
- Beaty, R. E., Benedek, M., Kaufman, S. B., & Silvia, P. J. (2015). Default and executive network coupling supports creative idea production. *Scientific Reports*, 5, 10964.
- Beaty, R. E., Benedek, M., Silvia, P. J., & Schacter, D. L. (2016). Creative cognition and brain network dynamics. *Trends in Cognitive Sciences*, 20, 87–95.
- Beaty, R. E., Christensen, A. P., Benedek, M., Silvia, P. J., & Schacter, D. L. (2017). Creative constraints: Brain activity and network dynamics underlying semantic interference during idea production. *NeuroImage*, 148, 189–196. <https://doi.org/10.1016/j.neuroimage.2017.01.012>.
- Beaty, R. E., Silvia, P. J., Nusbaum, E. C., Jauk, E., & Benedek, M. (2014). The role of associative and executive processes in creative cognition. *Memory & Cognition*, 42, 1186–1195.
- Bendetowicz, D., Urbanski, M., Aichelburg, C., Levy, R., & Volle, E. (2017). Brain morphometry predicts individual creative potential and the ability to combine remote ideas. *Cortex; a Journal Devoted To the Study of the Nervous System and Behavior*, 86, 216–229.
- Benedek, M., Beaty, R. E., Jauk, E., Koschutnig, K., Fink, A., Silvia, P. J., et al. (2014a). Creating metaphors: The neural basis of figurative language production. *NeuroImage*, 90, 99–106.
- Benedek, M., Jauk, E., Beaty, R. E., Fink, A., Koschutnig, K., & Neubauer, A. C. (2016). Brain mechanisms associated with internally directed attention and self-generated thought. *Scientific Reports*, 6, 22959.
- Benedek, M., Jauk, E., Fink, A., Koschutnig, K., Reishofer, G., Ebner, F., et al. (2014b). To create or to recall? Neural mechanisms underlying the generation of creative new ideas. *NeuroImage*, 88, 125–133.
- Benedek, M., Jauk, E., Sommer, M., Arendasy, M., & Neubauer, A. C. (2014c). Intelligence, creativity, and cognitive control: The common and differential involvement of executive functions in intelligence and creativity. *Intelligence*, 46, 73–83.
- Benedek, M., Kenett, Y., Umdasch, K., Anaki, D., Faust, M., & Neubauer, A. (2017). How semantic memory structure and intelligence contribute to creative thought: A network science approach. *Thinking & Reasoning*, 23, 158–183. <https://doi.org/10.1080/13546783.2016.1278034>.
- Benedek, M., Könen, T., & Neubauer, A. C. (2012). Associative abilities underlying creativity. *Psychology of Aesthetics, Creativity, and the Arts*, 6, 273–281.
- Benedek, M., Mühlmann, C., Jauk, E., & Neubauer, A. C. (2013). Assessment of divergent thinking by means of the subjective top-scoring method: Effects of the number of top-ideas and time-on-task on reliability and validity. *Psychology of Aesthetics, Creativity, and the Arts*, 7, 341–349.
- Benoit, R. G., & Schacter, D. L. (2015). Specifying the core network supporting episodic simulation and episodic memory by activation likelihood estimation. *Neuropsychologia*, 75, 450–457.
- Binder, J. R., & Desai, R. H. (2011). The neurobiology of semantic memory. *Trends in Cognitive Sciences*, 15, 527–536.
- Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*, 19, 2767–2796.
- Chen, Q., Beaty, R. E., Wei, D., Yang, J., Sun, J., Liu, W., et al. (2017). Longitudinal alterations of frontoparietal and frontotemporal networks predict future creative cognitive ability. *Cerebral Cortex*. <https://doi.org/10.1093/cercor/bhw353> (in press).

¹ We reanalyzed the data with only half of the *Recall Common* trials (by removing every second trial from the design matrix) to ensure an equal amount of trials and objects per condition. This analysis revealed virtually the same results, suggesting that our findings are robust to variations of this design feature.

- Chrysikou, E. G., & Thompson-Schill, S. L. (2011). Dissociable brain states linked to common and creative object use. *Human Brain Mapping, 32*, 665–675.
- Chrysikou, E. G., Weber, M. J., & Thompson-Schill, S. L. (2014). A matched filter hypothesis for cognitive control. *Neuropsychologia, 62*, 341–355.
- Dale, A. M., & Buckner, R. L. (1997). Selective averaging of rapidly presented individual trials using fMRI. *Human Brain Mapping, 5*, 329–340.
- Diedrich, J., Benedek, M., Jauk, E., & Neubauer, A. C. (2015). Are creative ideas novel and useful? *Psychology of Aesthetics, Creativity, and the Arts, 9*, 35–40.
- Erhardt, E. B., Rachakonda, S., Bedrick, E. J., Allen, E. A., Adali, T., & Calhoun, V. D. (2011). Comparison of multi-subject ICA methods for analysis of fMRI data. *Human Brain Mapping, 32*, 2075–2095.
- Fink, A., Benedek, M., Koschutnig, K., Pirker, E., Berger, E., Meister, S., et al. (2015). Training of verbal creativity modulates brain activity in regions associated with language- and memory-related demands. *Human Brain Mapping, 36*, 4104–4115.
- Fink, A., Grabner, R. H., Benedek, M., Reishofer, G., Hauswirth, V., Fally, M., et al. (2009). The creative brain: Investigation of brain activity during creative problem solving by means of EEG and fMRI. *Human Brain Mapping, 30*, 734–748.
- Fink, A., Grabner, R. H., Gebauer, D., Reishofer, G., Koschutnig, K., & Ebner, F. (2010). Enhancing creativity by means of cognitive stimulation: Evidence from an fMRI study. *NeuroImage, 52*, 1687–1695.
- Fink, A., Weber, B., Koschutnig, K., Benedek, M., Reishofer, G., Ebner, F., et al. (2014). Creativity and schizotypy from the neuroscience perspective. *Cognitive, Affective & Behavioral Neuroscience, 14*, 378–387.
- Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., Van Essen, D. C., & Raichle, M. E. (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences of the United States of America, 102*, 9673–9678.
- Gilhooly, K. J., Fioratou, E., Anthony, S. H., & Wynn, V. (2007). Divergent thinking: Strategies and executive involvement in generating novel uses for familiar objects. *British Journal of Psychology, 98*, 611–625.
- Gonen-Yaacovi, G., de Souza, L. C., Levy, R., Urbanski, M., Josse, G., & Volle, E. (2013). Rostral and caudal prefrontal contribution to creativity: A meta-analysis of functional imaging data. *Frontiers in Human Neuroscience, 7*, 465.
- Grefkes, C., Weiss, P. H., Zilles, K., & Fink, G. R. (2002). Crossmodal processing of object features in human anterior intraparietal cortex: An fMRI study implies equivalencies between humans and monkeys. *Neuron, 35*, 173–184.
- Hassabis, D., & Maguire, E. A. (2007). Deconstructing episodic memory with construction. *Trends in Cognitive Sciences, 11*, 299–306.
- Jung, R. E., Mead, B. S., Carrasco, J., & Flores, R. A. (2013). The structure of creative cognition in the human brain. *Frontiers in Human Neuroscience, 7*, 330.
- Kaufman, J. C., Plucker, J. A., & Baer, J. (2008). *Essentials of creativity assessment*. John Wiley & Sons.
- Kleibeuker, S., Koolschijn, P. C., Jolles, D., De Dreu, C., & Crone, E. A. (2013). The neural coding of creative idea generation across adolescence and early adulthood. *Frontiers in Human Neuroscience, 7*, 905.
- Koestler, A. (1964). *The act of creation*. New York: Macmillan.
- Leon, S. A., Altmann, L. J., Abrams, L., Gonzalez Rothi, L. J., & Heilman, K. M. (2014). Divergent task performance in older adults: Declarative memory or creative potential? *Creativity Research Journal, 26*, 21–29.
- Liu, S., Erkkinen, M. G., Healey, M. L., Xu, Y., Swett, K. E., Chow, H. M., et al. (2015). Brain activity and connectivity during poetry composition: Toward a multidimensional model of the creative process. *Human Brain Mapping, 36*, 3351–3372.
- Madore, K. P., Addis, D. R., & Schacter, D. L. (2015). Creativity and memory: Effects of an episodic specificity induction on divergent thinking. *Psychological Science, 26*, 1461–1468.
- Mednick, S. A. (1962). The associative basis of the creative process. *Psychological Review, 69*, 220–232.
- Mullally, S. L., & Maguire, E. A. (2014). Memory, imagination, and predicting the future. A common brain mechanism? *The Neuroscientist: a Review Journal Bringing Neurobiology, Neurology and Psychiatry, 20*, 220–234.
- Pinho, A. L., Ullén, F., Castelo-Branco, M., Fransson, P., & de Manzano, Ö. (2016). Addressing a paradox: Dual strategies for creative performance in introspective and extrospective networks. *Cerebral Cortex, 26*, 3052–3063.
- Runco, M. A., & Jaeger, G. J. (2012). The standard definition of creativity. *Creativity Research Journal, 24*, 92–96.
- Sarter, M., Givens, B., & Bruno, J. P. (2001). The cognitive neuroscience of sustained attention: Where top-down meets bottom-up. *Brain Research Reviews, 35*, 146–160.
- Schacter, D. L., Addis, D. R., & Buckner, R. L. (2007). Remembering the past to imagine the future: The prospective brain. *Nature Reviews. Neuroscience, 8*, 657–661.
- Schacter, D. L., Addis, D. R., Hassabis, D., Martin, V. C., Spreng, R. N., & Szpunar, K. K. (2012). The future of memory: Remembering, imagining, and the brain. *Neuron, 76*, 677–694.
- Silvia, P. J. (2011). Subjective scoring of divergent thinking: Examining the reliability of unusual uses, instances, and consequences tasks. *Thinking Skills and Creativity, 6*, 24–30.
- Silvia, P. J. (2015). Intelligence and creativity are pretty similar after all. *Educational Psychology Review, 27*, 599–606.
- Silvia, P. J., Beaty, R. E., & Nusbaum, E. C. (2013). Verbal fluency and creativity: General and specific contributions of broad retrieval ability (Gr) factors to divergent thinking. *Intelligence, 41*, 328–340.
- Silvia, P. J., Nusbaum, E. C., & Beaty, R. E. (2017). Old or new? Evaluating the old/new scoring method for divergent thinking tasks. *The Journal of Creative Behavior, 51*, 216–224.
- Simonton, D. K. (2012). Taking the US Patent Office creativity criteria seriously: A quantitative three-criterion definition and its implications. *Creativity Research Journal, 24*, 97–106.
- Spreng, R. N., DuPre, E., Selarka, D., Garcia, J., Gojkovic, S., Mildner, J., et al. (2014). Goal-congruent default network activity facilitates cognitive control. *Journal of Neuroscience, 34*, 14108–14114.
- Spreng, R. N., Mar, R. A., & Kim, A. S. N. (2009). The common neural basis of autobiographical memory, prospection, navigation, theory of mind, and the default mode: A quantitative meta-analysis. *Journal of Cognitive Neuroscience, 21*, 489–510.
- Stark, A., & Zohary, E. (2008). Parietal mapping of visuomotor transformations during human tool grasping. *Cerebral Cortex, 18*, 2358–2368.
- Stein, M. I. (1953). Creativity and culture. *The Journal of Psychology, 36*, 311–322.
- Szpunar, K. K. (2010). Episodic future thought: An emerging concept. *Perspectives on Psychological Science, 5*, 142–162.
- Takahama, S., Miyauchi, S., & Saiki, J. (2010). Neural basis for dynamic updating of object representation in visual working memory. *NeuroImage, 49*, 3394–3403.
- Tunik, E., Rice, N. J., Hamilton, A., & Grafton, S. T. (2007). Beyond grasping: Representation of action in human anterior intraparietal sulcus. *NeuroImage, 36*, T77–T86.
- Vilberg, K. L., & Rugg, M. D. (2008). Memory retrieval and the parietal cortex: A review of evidence from a dual-process perspective. *Neuropsychologia, 46*, 1787–1799.

- Wagner, A. D., Shannon, B. J., Kahn, I., & Buckner, R. L. (2005). Parietal lobe contributions to episodic memory retrieval. *Trends in Cognitive Sciences*, 9, 445–453.
- Whitfield-Gabrieli, S., & Nieto-Castanon, A. (2012). Conn: A functional connectivity toolbox for correlated and anticorrelated brain networks. *Brain Connectivity*, 2, 125–141.
- Yeo, B. T., Krienen, F. M., Sepulcre, J., Sabuncu, M. R., Lashkari, D., Hollinshead, M., et al. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology*, 106, 1125–1165.
- Zabelina, D. L., & Andrews-Hanna, J. R. (2016). Dynamic network interactions supporting internally-oriented cognition. *Current Opinion in Neurobiology*, 40, 86–93.