Building Individual Semantic Networks and Exploring their Relationships with Creativity

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Abstract

The associative theory of creativity suggests that creative abilities rely on the organization of semantic associations in memory. Recent research has demonstrated that semantic network methods allow testing this hypothesis. The aim of the current study was to investigate the properties of semantic networks at the individual level, in relation to creative abilities. Semantic judgement ratings were used to estimate individual semantic networks, whose topological properties measured by several graph metrics were correlated with individual creativity scores. We found a correlation between the theoretical semantic distance of our stimuli and the relatedness ratings given by the participants, demonstrating the validity of our approach. Importantly, we found a close relationship between creative abilities assessed by an achievement questionnaire and divergent thinking tasks and individual semantic network metrics, replicating and extending previous similar findings.

Keywords: creativity; semantic networks; network science; associative thinking

Introduction

The associative theory of creativity hypothesizes that creative abilities are related to individual differences in the organization of semantic associations in memory (Mednick, 1962). In support of this theory, several findings showed that more creative individuals had less common word associations or a less constrained organization of semantic associations (Beaty et al., 2014; Bendetowicz et al., 2017; Benedek et al., 2012; 2017; Kenett et al., 2014; Rossmann & Fink, 2010; Volle, 2018) and that in brain-damaged patients, rigid semantic associations were associated with poor creative abilities (Bendetowicz et al., 2018; Ovando-Tellez et al., 2019). Thus, the properties of semantic associations play a critical role in the cognitive processes that bring forth original ideas. Recently, computational methods exploring semantic memory structure in creativity are paving the way to uniquely study its role in creativity. One such computational approach is based on network science methodologies (Kenett, 2018; Kenett & Faust, 2019).

Network science is based on mathematical graph theory, providing quantitative methods to investigate complex systems, such as semantic memory, as networks (Siew et al., in press). In semantic networks, concepts or words are represented as nodes that are connected to each other by edges (denoting semantic similarity between concepts). The few studies that have applied semantic networks in the field of creative thinking indicate that studying the properties of semantic networks is a promising approach to explore creativity (Kenett, 2018; Kenett & Faust, 2019). For example, Kenett et al. (2014) investigated the semantic networks of low and high creative participants, based on free associations generated by both groups to a list of cue words. The authors showed that the semantic networks of low creative participants were less connected and more spread out compared to high creative participants.

However, aggregating over participants into groups may obscure individual differences related to creativity. To address this issue, Benedek et al. (2017) developed a new method to estimate individual semantic networks, based on semantic judgment ratings. Participants rated the relations between all possible pairs of 28 cue words, chosen to represent seven different categories. These relatedness ratings served as a proxy to the organization of these cue words in an individual's semantic memory. The authors showed how individual-based semantic network metrics correlated with individual-based creativity scores (Benedek et al., 2017) for specific types of filtered networks. However, in their study, the authors subjectively selected such cue words, and also applied a specific task, the Alternative Uses Task (AUT), to measure creative ability.

The general aim of the current study was to replicate and extend the relationships between the properties of individual semantic networks and creative abilities found by Benedek et al. (2017). Individual semantic networks were estimated using a modified version of Benedek et al. (2017) in which we controlled for the selection of the cue words based on a computational method. Participant's creativity was more extensively assessed via a creativity battery, including the

AUT used in the original study, a problem-solving task, and a creative achievement questionnaire. Specific network metrics of the individual semantic networks were computed and were correlated with the obtained creative scores.

Materials and Methods

Participants

Twenty-three healthy individuals aged between 22 and 37 years (26.96 ± 4.25) were included in the study. Participants were French-native speakers, right-handed with no neuropsychiatric disease. Two participants were excluded from the graph analysis because they rated >70% of word pairs as unrelated. This study was approved by the French ethical committee Sud Mediterrannée IV. Participants gave written consent and were paid for their participation.

General Overview

The study was composed of two parts. In the first part, the associative judgment task (AJT) was devised to estimate individual's semantic networks. The AJT was adapted from Benedek et al. (2017) by constructing new verbal material controlled for linguistic and semantic properties. In the AJT task, participants are asked to rate the semantic relatedness of pairs of words. In the second part, participants performed the AJT and a set of creativity tasks. AJT ratings were used to estimate the individual AJT-based semantic networks and network metrics were correlated with creative scores.

Part 1: The Associative Judgment Task (AJT)

We first used computational methods in order to develop and select a new set of cue words to be used in the AJT, accounting and controlling for semantic and linguistic properties. This was achieved by 1) estimating a large French semantic network, based on a large database of semantic association norms in French, and 2) by selecting a set of cue words, based on the properties of this network.

Creation of a French Semantic Network. To construct the French version of the AJT, we estimated a French semantic network of 1,081 words, based on French verbal association norms (Debrenne, 2011; http://dictaverf.nsu.ru/dictlist). This dataset was collected by asking French native speakers to provide the first word that came to mind after receiving a cue word. We selected words for which at least 400 participants provided a response. The final data contains 1,081 cue words and 26,268 responses from the participants.

The French semantic network was estimated using a network approach developed to analyze free association data (Kenett et al., 2014). According to this approach, each node represents a cue word and edges between nodes represent the association between these nodes. These associations represent the similarity profiles across any pair of cue words, i.e., the overlap of associative responses generated by the sample to each of the cue words.

The network was estimated in the following way: First the associative responses were preprocessed to standardize responses (correction of typos, elimination of non-words and articles, and spelling homogenization). Second, a data matrix was constructed such that each column is a cue word, and each row is a unique associative response. Thus, each cell denotes how many participants generated response *i* to cue word *j*. Third, the correlation between any pair of cue words was calculated using Pearson's correlation. This resulted in a 1,081 by 1,081 matrix where each cell denotes the semantic correlation between node *i* and node *j*. To minimize noise and possible spurious associations, we finally applied the planar maximally filtered graph filter (Kenett et al., 2014). To examine the structure of the networks, the edges were binarized so that all edges were converted to a uniform weight (i.e., 1). This allowed us to compute the shortest path between nodes in the network, serving as the theoretical semantic distance between them (Kenett et al., 2017).

Selection of AJT Stimuli. To select the verbal material to be used in the AJT, we developed a new computational method that allowed us to objectively select words with specific associative and linguistic properties from the French semantic network.

From the French semantic network, hierarchical tree structures were created recursively, using each node as a seed and searching for its neighbors. For each iteration, the neighbors of the neighbor's nodes were searched. In total we performed 4 iterations, considering that Kenett et al. (2017) demonstrated that most participants judged as unrelated the words separated by more than 4 steps in a force choice task. However, this tree procedure generated nodes that were separated by more than 4 steps when they belong to distinct branches, which allowed us to also generate word pairs that will be likely judged as unrelated. To avoid having one central node related to all the others by 4 steps or less, the initial seed node was removed.

The computation returned several solution trees among which one was selected for the AJT task based on the following criteria. First, for experimental reasons, the total number of nodes in the tree was limited to 35, i.e., 595 possible pair combinations between all words that had to be rated by the participants during the experiment. Second, we computed the *theoretical semantic distance* for all possible word pairs in term of the number of steps separating them in all of the trees. We selected the tree that optimized the proportion of pair words separated by 1, 2, 3, 4, or 5 or more steps. The selected tree contained a set of 35 words involving 595 possible word pairs with semantic distances distributed as follow: 10% of 1 step, 18% of 2 steps, 28% of 3 steps, 26% of 4 steps, 15% of 5 steps and 3% of 6 steps.

Part 2: AJT-based networks and creativity

Procedure of the AJT. Participants were presented successively with all the 595 combinations of pairs of the 35 selected words and were asked to rate their semantic relatedness, using a visual scale ranging from 0 (unrelated) to 100 (strongly related). Each trial started with the display of the word pair and a visual scale presented at the center of the

screen. After 2 seconds, the slider appeared in the middle of the scale. Participants could then freely move the cursor on the scale using a mouse and validated their response by a left click. They had to respond within 2 seconds. The final position of the slider in the scale after validation was considered as the semantic relatedness rating (Fig. 1).

In total, participants performed 6 different runs of 100 trials each (except the last run with 95 trials). Each run was composed of 4 blocks of 25 trials and separated by 20 seconds rest periods with a fixation cross. The trials were pseudo-randomly ordered within blocks with the constraint that each block contained a similar proportion of word pairs of each theoretical step. This order was fixed across participants. Before starting the task, participants performed a short practice. In addition, we checked that all participants were familiar with the 35 AJT words.

Relatedness ratings were coded for each participant and values were averaged separately for each theoretical distance and overall (see Fig. 2).

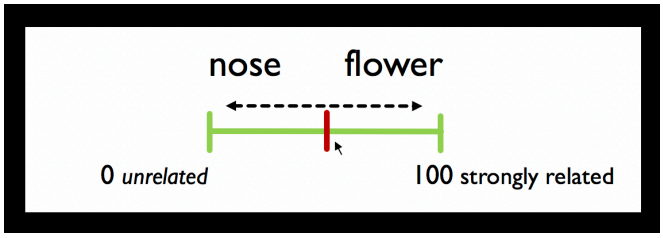

Fig. 1: Schematic representation of an AJT trial.

Estimating AJT-based individual semantic networks. Participant ratings of the word pairs during the AJT task served as a proxy of the organization of these words in their individual semantic network. We created a *n* by *n* matrix in which *n* represented the words used in the AJT task and each matching cell represented the semantic relatedness judgement given by the participant for these two words.

We employed two network filtering methods, one that had revealed significant relationships to creative abilities in previous work (Benedek et al., 2017) and a more conservative method that keeps more information in the network. In the first filtering method, we applied a fixed minimum relatedness threshold to the data and only edges with a weight of at least 50 were maintained. Since the value of 50 is the middle of the AJT scale, only edges corresponding to moderate to high semantic relatedness were kept and set to 1 whereas all the others were removed, resulting in an unweighted undirected network (UUN). In the second filtering method, all the edges were kept with their weight, so it preserved the variability in semantic judgments and resulted in a weighted undirected network (WUN). In this graph, each edge was weighted by the relatedness judgement given by the participant. For both networks, when the participant judged two words as unrelated (rating = 0), the two corresponding nodes had no edges linking them.

Based on the metrics previously related to creative abilities (Benedek et al., 2017; Kenett et al., 2014), we computed the following network metrics to characterize the structure of an individuals' semantic networks: the clustering coefficient (*CC*), the average shortest path length (*ASPL*), the diameter of the graph (*D*), smallworldness (*S*), betweenness centrality (*BC*), and modularity (*Q*). *CC* measures the degree to which nodes in a graph tend to cluster together. *ASPL* measures the average shortest number of steps that separate any pair of nodes, and *D* represents the longest path in the network. S is computed as a ratio between *CC* and *ASPL*. *BC* corresponds to the fraction of all shortest paths in the network that contain a given node. *Q* refers to the percentage of the network that is integrated into small-community structures. Analyses were performed with the Brain Connectivity Toolbox in Matlab (Rubinov & Sporns, 2010).

Creative Assessment. Creativity was assessed using the Combined Associates Task (CAT), the Alternative Uses Task (AUT) and the Inventory of Creative Activities and Achievements (ICAA).

The CAT is an adaptation of the Remote Associates Task (Mednick, 1962) developed by Bendetowicz et al. (2017; 2018) and assesses the ability to form new combinations between remotely associated words. In this task, participants are asked to find a word linked to three cue words with no apparent associations in a maximum of 30 seconds. CAT defines close and distant trials depending on the semantic distance between the cue words and the solution. 40 trials with an equal number of close and distant trials were administered. To quantify the data, four scores were analyzed. *CAT_Solving* is the sum of correct responses. *CAT_Close* and *CAT_Distant* correspond to the sum of correct responses in close and distant trials respectively, and *CAT_Index* corresponds to the difference in performance between distant and close trials, corrected by the averaged performance and was shown to reflect creative processes (Bendetowicz et al., 2017).

During ***the AUT*****,** participants were asked to generate original uses for a common object in three minutes. At the end of the three minutes, the participants selected their two most creative responses, as top-two scoring has been observed to be an effective approach to assess creativity (Benedek et al., 2013; Silvia et al., 2008). This procedure was repeated for three objects: tire, bottle and knife. The corresponding nouns naming the objects were presented on the screen during the 3 minutes. Scores for fluency and originality were assessed for each object. *AUT_Fluency* refers to the total number of ideas generated by the participant and *AUT_Originality* counts the number of infrequent ideas (given by less than 5% of the participants) among the top-two ideas of the participant.

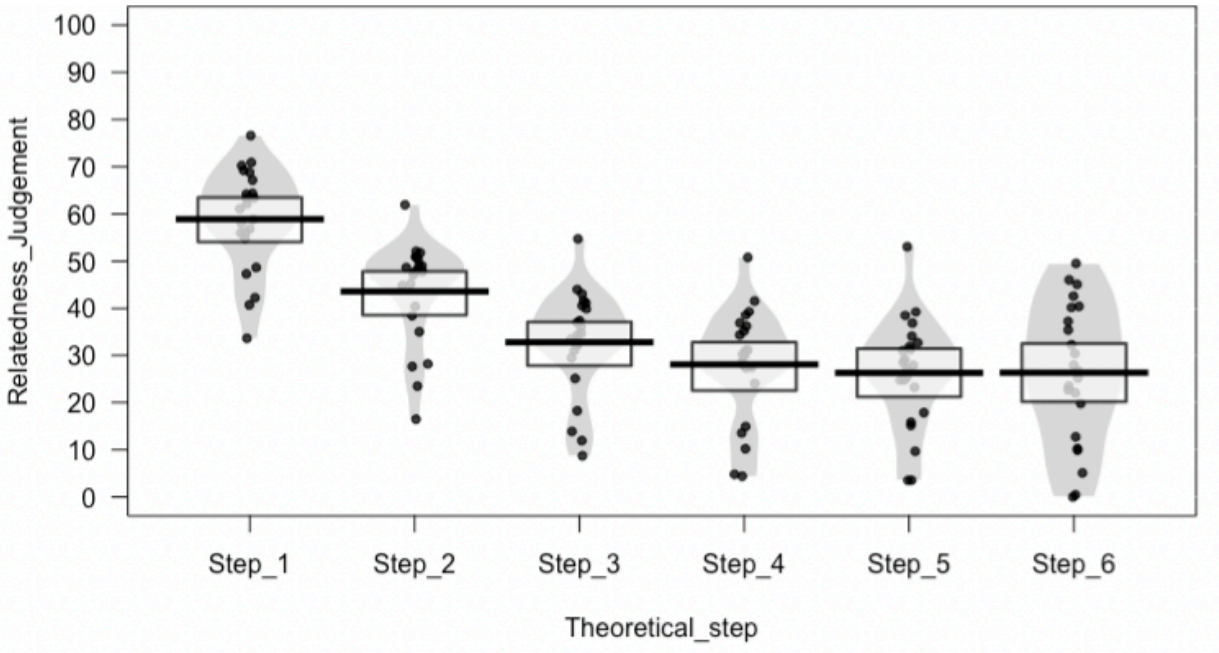

Fig. 2: AJT Task validation. Relatedness ratings of the participants are plotted against theoretical distance. X-axis - Theoretical distance according to the French semantic graph. Y-axis - Relatedness ratings given by the participants. Dots symbolize individual mean response ratings; bars show the mean across participants; white bands correspond to the inference representing the 95% of a Bayesian highest density interval; and the grey area displays the smooth density distribution.

The ***ICAA*** questionnaire was used to quantify everyday creative activities and achievements (Diedrich et al., 2018). This questionnaire contains two parts. In the first part, participants answered questions focused on 8 different specific domains. For each domain, the quantification considered aspects related to how many times the participant had carried out a certain activity over the last 10 years, the level of achievement they have attained in the domain and how many years they have engaged in the specific domain. In the second part, participants described the five most creative achievements in their life. The scores *ICAA_1* (creative activities) and *ICAA_2* (creative achievements) were obtained as the total score for part one and part two respectively.

Results

Relatedness Judgments and Theoretical Semantic Distance

Relatedness ratings within each participant ranged from 0 to 100 indicating that participants used the full scale to rate relationships. Overall mean relatedness ratings across participants ranged from 13.49 to 54.02, with a mean of 33.22 (± 8.66) and median of 34.08. For each participant, we found a significant negative correlation between the relatedness ratings and the theoretical distance ($p < .001$) with a correlation coefficient from -.2 to -.3 (Fig. 2).

AJT-based Network Metrics and Creativity

The network metrics were correlated to the creativity measures using Kendall Tau-b. These correlations were done separately for the WUN and UUN metrics. Fig. 3 shows an illustration of two WUN networks, from a high creative and a low creative participant, chosen among participants with respectively the highest vs poorest scores in both *AUT_Originality* and *ICAA_1*.

Significant correlations were found between several metrics from the WUN networks and creativity scores. *ICAA_1* negatively correlated with *D* ($\tau = -.32$, $p < .05$) and *ASPL* ($\tau = -.34$, $p < .05$) and positively with *S* ($\tau = .32$, $p < .05$). *AUT_Originality* negatively correlated with *D* ($\tau = -.45$, $p < .01$), *ASPL* ($\tau = -.41$, $p < .05$) and *BC* ($\tau = -.39$, $p < .05$) and positively correlated with *CC* ($\tau = .35$, $p < .05$). Similar correlations were found between several metrics from the UUN networks and creativity scores. *ICAA_1* correlated negatively with S ($\tau = -.41$, $p < .05$). *AUT_Originality* negatively correlated with *D* ($\tau = -.51$, $p < .01$), *ASPL* ($\tau = -.44$, $p < .05$), *BC* ($\tau = -.46$, $p < .01$), *S* ($\tau = -.49$, $p < .01$) and *Q* ($\tau = -.38$, $p < .05$). All *p*-values reported above are uncorrected and did not survive an FDR correction.

AJT behavior and Creativity Scores

To test whether creativity also relates more directly to AJT behavioral measures (Rossman & Fink, 2010), Pearson correlations were computed between the creativity scores and AJT relatedness ratings, overall and separately for each

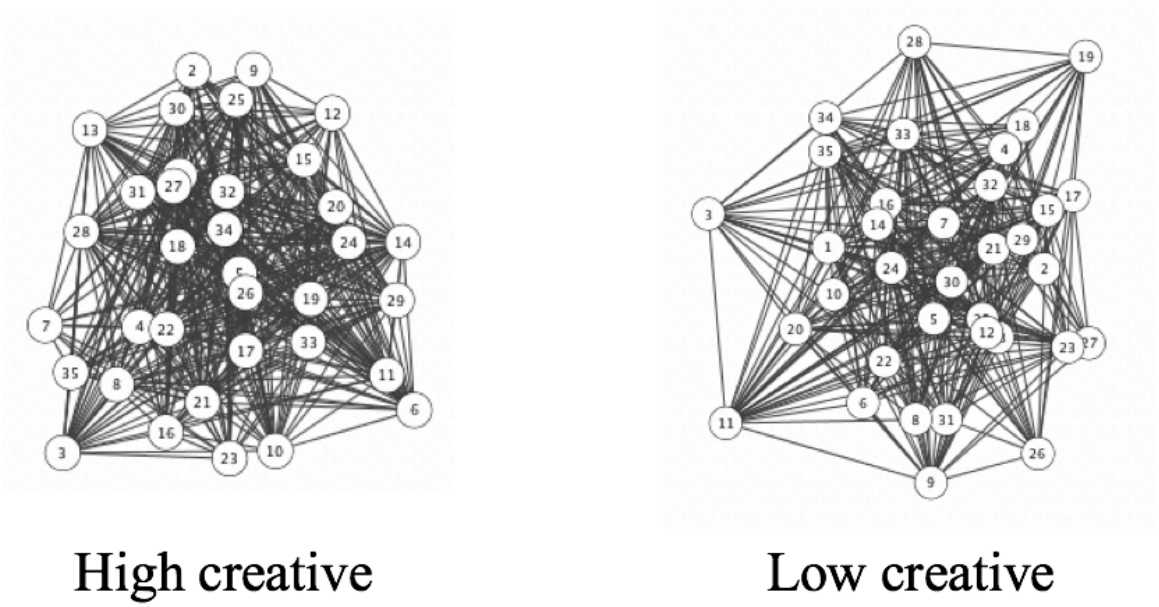

Fig. 3: Example individual semantic networks of a low and high creative participant (weighted undirected networks). Circles represent nodes (single words, labelled as numbers), grey lines represent the edges connecting the nodes, with higher weighted edges having a shorter length representing higher semantic relatedness. The high and low creative participants were chosen among participants with the highest and lowest scores in creativity assessments, respectively (*AUT_Originality* and *ICAA 1*).

theoretical step from 1 to 6. The mean AJT relatedness ratings correlated positively with *AUT_Originality*, $\rho(19) = .54$, $p < .05$: Participants judging word pairs as more related overall produced more original ideas at the AUT task. Correlations with the other creativity scores were not significant.

When analyzed separately for each theoretical distance, AJT relatedness judgement correlated with *AUT_Originality* for word pairs separated by 6 steps, $\rho(19) = .55$, $p < .01$, 5 steps, $\rho(19) = .46$, $p < .05$, 4 steps, $\rho(19) = .46$, $p < .05$, 3 steps, $\rho(19) = .49$, $p < .05$ and 2 steps, $\rho(19) = .56$, $p < .01$. Participants judging theoretically distant word pairs (step >= 2) as more related produced more original ideas at the AUT task. AJT relatedness ratings for close word pairs (1 step apart) correlated positively with *CAT_Solving*, $\rho(19) = .50$, $p < .05$, and *CAT_Close*, $\rho(19) = .55$, $p < .001$: Participants judging theoretically close word pairs (1 step apart) as more related were better at combining word associates and solved more CAT trials. No statistical results survive FDR correction for multiple comparisons.

Discussion

This study aimed to investigate the link between individual differences in the organization of semantic associations and creativity using computational methods based on graph theory. Individual semantic networks were estimated using an adapted version of the method from Benedek et al. (2017) by controlling the selection of the words based on computational methods. To this purpose, we first estimated a unique and large-scale semantic network in French. Next, we developed a method allowing to select a set of words in French while controlling for their semantic distance. Then, the selected words were used in a semantic relatedness judgement task and these relatedness ratings were used to estimate individual semantic networks. Several metrics characterizing the structure of these networks were computed and related to creative assessment scores.

Our results showed that the theoretical semantic distance correlated with the relatedness judgments of the participants, thus converging with the results of Kenett et al. (2017). Theoretical distance relies on the properties of a semantic network estimated from a free verbal association task submitted to a large number of independent volunteers and from the similarity between the generated associates of all cue words. This semantic network allows to measure a theoretical distance as the number of steps separating two nodes in the network. That this measure was strongly related to the subjective similarity judgement of our participants between these cue words validate the use of path length computed on such semantic network as a measure of semantic distance (also converging with results from Kenett et al., 2017). However, it is important to note that while the correlations were highly significant, the Kendall τ coefficients were of moderate size (mean of $\pm$ .22). One possibility would be that the relationship between the theoretical distance and rated distance between selected stimuli may not be linear across the full range of steps. In addition, other factors could impact these subjective relatedness ratings. For instance, subjective ratings showed a high inter-individual variability that could in part be explained by creative abilities, as indicated in the second part of our study.

The next step of the current study consisted of a behavioral experiment aiming to examine the relationships between the organization of semantic memory and creative abilities. The findings showed that some network metrics for both WUN and UUN networks were related to creativity measures including the originality of ideas generated during the AUT (*AUT_Originality*) and the creative activities in life assessed with ICAA (*ICAA_1*). However, those network metrics were not significantly correlated to the number of ideas generated in the AUT (*AUT_Fluency*) and creative achievements (*ICAA_2*) measured with the same tasks, nor to CAT scores.

Indeed, the results showed that participants with more original ideas in the AUT and/or more creative activities in their real life (*ICAA_1*), exhibit WUN networks that are less spread out (shorter *D* and *ASPL*), were more clustered (higher *CC*), showed greater small-world connective properties (higher *S*) and the nodes tended to have a more homogeneous connective role in the network (lower *BC*). Similarly, AJT-based UUN networks were also less spread out with shorter path length, less modular (lower *Q*) and with uniform nodes (lower *BC*) but with reduced small-world properties (*S*) in more creative participants.

Importantly, these findings replicate and expand the results from Benedek et al. (2017) who used UUN networks and showed similar correlations between *CC* and *ASPL* metrics and AUT; we additionally observed correlations between the AUT and other metrics (*BC*, *Q*, *D*). In WUN networks additional correlations were shown between network metrics (*D* and *ASPL*) and *ICAA_1*. These correlations indicate that the organization of semantic memory measured by network metrics is also a relevant factor in real life creativity.

Overall, the current findings suggest that more creative participants exhibit a more clustered and densely connected semantic network whereas less creative participants have a more spread out and fragmented network. These results are in line with the few previous studies that examined semantic memory and creativity (Benedek et al., 2017; Kenett et al., 2014; 2018; Kenett & Faust, 2019). Together these studies strengthen the view that exploring the organization of semantic associations using individual networks is both relevant and valuable for the neuroscience of creativity and support the associative theory of creativity.

Additionally, our method allows us to explore the relationships between AJT ratings and creativity measures. The AJT ratings averaged across all theoretical distances and separately for each theoretical distance greater than 1 was positively correlated with originality in AUT. This finding indicates that participants who produced more original ideas also identified word pairs as more related, especially for pairs of words being theoretically more distant. This result is consistent with Rossmann and Fink (2010) that showed a positive relationship between originality and the evaluated associative distance between unrelated word pairs. These findings suggest that creative people are able to perceive connections between concepts that others may not see. Conversely, the mean AJT rating for theoretically close word pairs (1 step apart) positively correlated with the total number of correct responses in CAT when considering all trials (*CAT_Solving*) or close trials only (*CAT_Close*). Participants who found close links in the CAT also judged theoretically close pairs as highly related. However, contrary to what was expected, the correlations with AJT ratings failed to reach significance when considering distant trials only (*CAT_Distant*) or the difference in performance between distant and close trials (*CAT_Index*). It is possible that distant trials involve additional processes that are less dependent on semantic associations (Bendetowicz et al., 2018). We cannot rule out that the small number of CAT trials used in this experiment may have influenced this result.

Finally, our results indicate that network metrics provide insight why people rate concepts as more or less related and that they are relevant quantitative measures to study creativity. However, statistical analyses revealed that no correlation with creativity scores survived the corrections for multiple comparisons. The small sample size may explain the lack of power, and more participants will be included in this study to address this issue. Nevertheless, the trends in the results and their consistency with previous studies are encouraging. Overall, the findings suggest that exploring individual semantic networks based on a controlled verbal material is a promising approach to study creativity.

Conclusions and Perspectives

To conclude, our data indicate a close relationship between the organization of semantic associations represented by semantic networks and creative abilities. Although the results will need to be confirmed in a larger sample, which is an ongoing project, the current study is consistent with previous studies performed in this field and offers improvements in semantic network methods. Our results are notably in agreement with previous studies that showed a link between creative abilities and the ability to make semantic connections between unrelated concepts. Developing new methods to measure the ability to make new semantic connections is an important challenge to better understand the mechanisms of creative cognition (Benedek & Fink, 2019). The analysis of individual semantic networks is one of the most promising approaches to achieve this goal.

The results of this study also offer interesting hypotheses to test regarding the brain substrates that underlie creative abilities. For instance, the same paradigm can be combined with functional MRI to explore how brain network activity and connectivity covary with the ability to connect distant concepts as measured by semantic network metrics. Moreover, graph theory can be used to study how brain network connectivity relates to the organization of semantic networks in the context of creativity.

Finally, the current study provides valuable insight regarding the fruitfulness of the newly created French semantic network. This network could be especially useful for measuring the semantic distance of words produced by participants in cognitive tasks or building new French task material in which semantic distance needs to be controlled.

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