Creativity involves the subjective valuation of ideas via the Brain Valuation System

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Abstract

Why do people have different opinions regarding who the best musical artist is? While neuroscience of creativity consensually defines creativity as producing something both original and adequate, how this is influenced by individual preferences remains unclear. Combining creative word-association and rating tasks, this study demonstrates that individuals assign subjective values to ideas, balancing originality and adequacy according to individual preferences and impacting their creative abilities. Functional Magnetic Resonance Imaging shows that subjective valuation is supported by the Brain Valuation System and that originality and adequacy are monitored via the Default Mode and the Executive Control Networks, respectively. Interestingly, the relative functional connectivity of the Default Mode and Executive Control Networks with the Brain Valuation System correlates with the relative balance of adequacy and originality in individuals' preferences. These results bridge a gap in the current literature by adding valuation to the incomplete behavioral and neural accounts of creativity, and offer perspectives on the influence of individual preferences on creative abilities.

1. Introduction

From global issues to daily struggles, humans consistently face new challenges and must rely on their creativity to solve them. In neuroscience, creativity is defined as the ability to form ideas that are both original and adequate (1). Original ideas are infrequent, unusual, novel or unique. Adequate ideas are appropriate, efficient, and useful; they comprise the requirements to fulfill their purpose. Despite an objective definition of *what* is creative, *how* individuals achieve a creative production remains unclear (2). Notably, two people will rarely come up with a similar solution to a problem nor prefer the same idea when asked for the best alternative (3,4). In fact, we still have a limited understanding of how individuals integrate originality and adequacy during creative performance and how individual preferences influence it.

The dominant neurocognitive view for creativity proposes a dual-process framework, decomposing the creative process into an idea-generation phase and an evaluation phase (5–13). In the generation phase, individuals form novel associations: they link seemingly unrelated concepts and produce a wide variety of potential solutions. This phase can be facilitated by memory structure (14), associative abilities (6,15,16) and cognitive flexibility (17), enabling individuals to navigate between different concepts during idea generation. In the evaluation phase, candidate ideas are assessed for originality and adequacy and selected according to the context. Evaluation processes are assumed to be deliberate and goal-directed and to rely on cognitive control mechanisms (11,12,16). Interestingly, the evaluation of originality and adequacy might vary between individuals and the tasks at hand (3). However, the exact computations at play during the two phases, especially during the evaluation of ideas, remain undetermined.

In this study, we conceptualize the evaluation step of creativity as a specific case of decision-making: similar to food options in dietary choices, creative options are compared, and the most satisfactory one is selected (18,19). We hypothesize that creative evaluation involves individual preferences and decision-making computations that methods from neuroeconomics can enable us to study. Specifically, we argue that creativity involves a valuation process.

In neuroeconomics, valuation consists of assigning a subjective value to an item - reflecting how valuable the item is, how much the subject likes it - and guides selection (20). Similarly, we propose that the subjective value of a creative idea reflects the satisfaction it provides and plays a crucial role in guiding idea selection. In a previous work (19), we demonstrated that creativity indeed involves valuation. In particular, that study first showed that the speed at which individuals produced ideas correlated to how much they liked them, suggesting that subjective valuation of ideas energizes creative production. Second, the value given to an idea was a function of its originality and adequacy, indicating that subjective valuation integrates the fundamental criteria of creativity. This integration varied across individuals, with some giving more weight to originality than adequacy. Finally, we showed that originality-inclined individuals yielded better creativity scores than adequacy-inclined, showing the impact of valuation patterns on creative abilities. Overall, this seminal study empirically established that valuation plays a central role in creativity. In the current study, we aim to identify the neural underpinnings of the valuation processes involved in creative thinking.

At the neural level, creativity research has found the generation and evaluation phases to be associated with the default mode network (DMN) and the executive control network (ECN), respectively (5,10,11). The DMN is a network composed of regions of the medial prefrontal cortex (mPFC) regions, the posterior cingulate cortex (PCC), the precuneus, the inferior parietal lobule (IPL) and the

temporal lobe. It is observed in individuals at rest, unfocused on their environment (21). The DMN also has a role in essential cognitive functions, including associative thinking, daydreaming, mind-wandering, and self-referential thoughts (22). In the context of creativity, the DMN has proven to be central to idea generation (16,23–27). In parallel, creativity research has found the evaluation phase of the dual process to be associated with the ECN. The ECN includes regions of the dorsolateral prefrontal cortex (dlPFC), the anterior cingulate cortex (ACC), the inferior parietal lobule (IPL) and the temporal lobe. It has been consistently associated with cognitive control, working memory processes, goal-directed behavior, task switching and decision-making (28). In creativity, research has shown that the ECN supports idea evaluation (10,16,23–26,29,30).
Interestingly, the ECN and DMN typically exhibit mutually exclusive activity depending on whether the task is internally or externally focused (31). However, in the context of creativity, their cooperation has been widely observed and appears to be essential for creative thinking and performance (5,11,32).

While focusing on the role of the ECN in evaluation, where originality and adequacy are encoded during creative thinking and how this information is used to guide creative performance remains unclear. Moreover, decision-making processes and their neural substrates have been overlooked, and a notable blind spot has emerged in our understanding of the neurocognitive bases of creative evaluation.

In neuroeconomics, research on the neural bases of decision-making processes shows that subjective values are encoded in the brain valuation system (BVS) (33,34). The BVS is one of the names given to the brain network for reward processing, which overlaps the reward system identified in animal literature (35). It comprises the ventromedial prefrontal cortex (vmPFC), the orbitofrontal cortex (OFC), and subcortical regions, particularly the ventral striatum (VS) and the ventral tegmental area (VTA). The valuation process in the BVS is both generic and automatic. Generic in the sense that the activity in the BVS correlates with the value of an object regardless of its nature. Automatic in that the value is encoded in the BVS even when an individual is evaluating another attribute, such as the age of a painting (34,36–38). Besides the BVS, the ECN is also engaged in decision-making processes: it ensures top-down control by adjusting the values of options based on the context of the decision (39). The ECN is also responsible for integrating the difference in values between options. This difference in values is referred to as the decision value, as it drives the selection process (40).

Based on its generic properties and its cooperation with the ECN, we hypothesize that idea valuation during creativity is supported by the BVS. This is consistent with several findings in creativity research, demonstrating the involvement of BVS regions (41–43) or dopaminergic modulation (44–47) in creativity. Despite these results and the overall recognized importance of motivation in creativity, its neural bases and the probable involvement of the BVS in creativity have been largely overlooked.

In summary, we propose to investigate the neural underpinnings of idea evaluation and valuation during creativity. Using functional Magnetic Resonance Imaging (fMRI), we expect to (i) demonstrate that the subjective value of an idea is encoded in the BVS and (ii) clarify where originality and adequacy are encoded in the brain during idea production.

To address these questions and hypotheses, we recruited forty participants who performed a creative word association task during an fMRI session. Participants also rated how likeable, original and adequate the associations were. We first replicated the behavioral results of our previous work

(Lopez-Persem et al., 2023), showing that valuation plays a role in creativity. Then, we identified the brain regions underlying the valuation of ideas and the encoding of originality and adequacy during the rating tasks. Based on these functional localizers, we determined whether and where subjective values, originality and adequacy were encoded in the brain when producing creative ideas in the word association task.

2. Results

The study consisted of several successive tasks (Figure 1): a Free Generation of Associate Task (FGAT), a likeability rating task and a choice task, all performed in an MRI, followed by an originality and adequacy rating task and a battery of creativity tests completed outside of the MRI. Thirty-eight subjects were included in the analyses (19 females, age = 26.5 ±4.0 (M±SEM), years of education = 16.5 ±1.9 (M±SEM)).

2.1. Behavioral results

In the FGAT-first condition, we asked participants to give the first word that came to mind when reading a cue word. In the "distant" condition, they had to give a word that was farther from the cue word, resulting in more creative associations than in the "first" condition (Figure 1B). Then, participants rated how much they liked the associations (the association's subjective value) and how original and adequate they found them on a scale of 0 to 100 (Figure 1C).

2.1.1. Individuals achieve better adequacy and originality when trying to be creative

To characterize participants' creative productions, we first explored the differences between FGAT "first" and "distant" responses, using the participants' adequacy and originality ratings. As expected, "first" associations were highly adequate and little original (adequacy rating = 84.7±1.4; originality rating = 34.2±1.7, M±SEM across participants), while "distant" associations were highly adequate and original (mean adequacy rating = 75.0±1.5; mean originality rating = 64.2±1.6). In addition, we found that the difference in originality between "first" and distant" associations was greater than the difference in adequacy (paired two-tailed t-test: $t(37)=10.3$, $p=2.10^{-12}$), indicating that "distant" associations were both original and adequate - i.e., creative - while "first" associations were mainly adequate (Figure 2A left).

Then, using an objective measure - i.e., the associative frequency of responses, measured with the dictionary of verbal associations "Dictaverf", we also found that "distant" responses were less frequent than "first" responses (paired two-tailed t-test: $t(37)=-25.9$, $p<.001$), confirming that the "distant" condition elicited more remote, creative ideas.

2.1.2. Individuals provide preferred responses faster

Then, we looked for a behavioral signature of preferences during idea production. We inspected response times (RT) in the FGAT, i.e., the thinking time between when the participant saw the cue word and when they pressed the button to give their response (Figure 1B).

We found that participants generated the ideas they liked faster than the ones they disliked in the "distant" condition ($RT_{distant}$ regressed against likeability: $\beta_{distant}=-0.20\pm0.03$, one-sample two-tailed t-test: $t(37)=-7.53$, $p=6.10^{-9}$) but not in the "first" condition (RT_{first} regressed against likeability: $\beta_{first}=0.05\pm0.05$, one-sample two-tailed t-test: $t(37)=1.11$, $p=0.3$). The effect of likeability on response times was significantly different between conditions (effect of likeability on "distant" versus "first" RT - i.e. $\beta_{distant}-\beta_{first}$: paired two-tailed t-test: $t(37)=-4.63$, $p=4.10^{-9}$, Figure 2A right). Note that this result holds when adding an additional regressor of squared normalized likeability as a proxy for confidence (48,49) (Supplementary Results).

Overall, the effect of likeability on the FGAT-distant response times suggests an implicit involvement of valuation during creative idea production. When generating ideas, participants intrinsically value them, which is reflected in their response time.

2.1.3. Individuals prefer responses that are both adequate and original

Next, we investigated how likeability judgements integrated adequacy and originality judgements. We observed that likeability increased with adequacy and originality: the more original and adequate an association was, the more it pleased participants (Figure 2B left).

We used the Constant Elasticity of Substitution (CES) model (50,51), which had provided the best fit in our previous study using the same experimental design (19). This model has two free parameters: alpha (α), which captures the weight given to originality relative to adequacy in the likeability ratings, and delta (δ), the preference for an equilibrium of originality and adequacy. We confirmed that the CES fitted the present dataset (mean fit ± standard error of the mean (SEM): r^2=0.42±0.03; one-sample two-tailed t-test: t(37)=15.43, p<0.001; Figure 2B right).

For each participant, we estimated the model's free parameters (hereafter referred to as valuation parameters). At the group level, we found that participants' likeability ratings resulted from a balanced trade-off of originality and adequacy (no preference for originality: α = 0.46±0.04, one-sample two-tailed t-test against 0.5: t(37)=-0.92, p=0.36; preference for equilibrium: δ = 0.44±0.21, one sample two-tailed t-test against 1: t(37)=-2.67, p=0.01). In other words, associations that were both original and adequate (rather than very original or very adequate) yielded higher likeability ratings at the group level. This suggests that valuation similarly and conjointly considers an idea's originality and adequacy, which is also consistent with the formal definition of creativity.

As a confirmatory analysis, we checked the relationship between the α parameter and the likeability of rare responses. Initially, we regressed likeability ratings against response frequency but found no significant effect at the group level ($\beta_{likeability\text{-}frequency}$=0.07±0.5, one-sample two-tailed t-test: t(37)=0.04, p=0.97; Figure S1A). However, post-hoc analyses on individual estimations of the α parameter revealed a high interindividual variability (coefficient of variation in α = 58%). Interestingly, this was linked to a strong negative correlation between the α parameter and the $\beta_{likeability\text{-}frequency}$ (r=-0.47, p=2.10^{-6}, Figure S1B). This correlation means that participants who favored originality also preferred rare associations, which nuances the null relationship between likeability and frequency at the group level and is consistent with our interpretation of the α parameter.

2.1.4. Individuals' preferences are related to creative abilities

Using a battery of tests and questionnaires, we estimated participants' creative abilities and investigated how they related to the valuation parameters of the CES using canonical correlation analysis.

We found one canonical variable showing significant dependence between the set of valuation parameters and the set of creative ability measures (r=0.52, p=0.025, Figure 3A). Both valuation parameters significantly contributed to the canonical variable (α: r=0.33, p=0.040; and δ: r=-0.50, p=0.001, Figure 3B) and among the creativity set, all but one of the creativity scores contributed to the canonical variable (associative fluency task score: r=0.34, p=0.035; CAT score: r=0.21, p=0.19; drawing task score: r=0.44, p=0.006; ICAA score: r=0.38, p=0.018, Figure 3C).

These results indicate that individuals' valuation pattern is related to their creative abilities: participants who valued originality (i.e., had a high α parameter) and its balance with adequacy (i.e., a low δ parameter) yielded higher scores in the battery of creativity tests.

2.2. Neuroimaging results

Behavioral results indicate that the production of creative associations involves participants' preferences. We then wanted to explore whether and which neural regions encoded subjective values (likeability) during idea production. Additionally, given that likeability relies on the adequacy and originality of ideas, we also explored the neural representations of those two dimensions. We first examined the relationship between each variable and neural activity during the likeability rating task to define functional localizers. Then, we investigated whether the identified brain regions were also involved in encoding those variables during creative idea production in the FGAT-distant condition.

2.2.1. Likeability ratings are encoded in the BVS during idea evaluation and production

Defining the functional localizer of likeability evaluation

We used a whole-brain parametric modulation approach to investigate the neural representation of likeability during the likeability rating task, with likeability ratings as regressors. The GLM we tested contains the likeability of the responses (from this likeability rating task) as a parametric modulator of a categorical boxcar regressor between the onset of the cue (i.e., the association) and the first button press to provide the likeability rating. We found a significant correlation between the associations' likeability ratings and the blood-oxygen-level-dependent (BOLD) signal in regions classically identified as parts of the BVS (Figure 4A): the vmPFC (peak Montreal Neurological Institute (MNI) coordinates: [x=-8 y=48 z=-10], t(37)=8.20, pFWE=5.10^{-15}) and the ventral striatum of the left ([-14, 22, 0], t(37)=7.55, pFWE=1.10^{-7}) and right hemisphere ([12, 22, -2], t(37)=6.98, pFWE=4.10^{-6}, see Table 1 for all significant clusters). This aligns with our hypothesis that likeability ratings are encoded in the BVS during idea valuation, similarly to any other item valuation.

Comparing the functional localizer of likeability evaluation to atlas functional networks

To confirm that likeability evaluation involved the BVS, we compared our localizer with the BVS (as defined by the term-based meta-analyses of the Neurosynth platform https://neurosynth.org/analyses/terms/reward/), as well as 7 intrinsic functional networks from the Yeo atlas (52). For this comparison, we quantified the number of voxels in common between our localizer and each atlas network (Figure 5). We found that the regions reflecting likeability ratings mostly overlapped with the BVS network (33 369 voxels out of 120 078, i.e. 28% of overlap), more so than with the other 7 networks, which aligned with our observations and hypotheses. For the following analyses, we defined the BVS region of interest (ROI) as the overlapping voxels of the functional localizer and the BVS Neurosynth network (the dark pink areas in Figure 5).

Locating the neural encoding of likeability during idea production

We performed ROI-based parametric modulation analyses on the FGAT-distant to determine whether likeability was also encoded in the BVS during the production of creative ideas and specify which regions in particular. The GLM we tested contains the likeability of the responses (obtained in the rating task) as a parametric modulator of a categorical boxcar regressor between the onset of the cue and the button press to provide the creative response. We found a significant correlation with likeability within the BVS ROI (set p-value=0.007; see Table 2 for details). Plus, when investigating the clusters within the ROI, we found a significant correlation between the likeability of the response

and the BOLD signal in the ventral striatum ([-14, 8, -14], t(37)=4.64, peak p-value (FWE)=0.015; Figure 4B), which confirms our hypothesis that valuation is at play during idea production via the encoding of likeability in the BVS. Note that this result was controlled for response times (Supplementary Results and Table S2).

Interestingly, the same GLM did not yield any significant results when applied to the FGAT-first condition (peak p-values (FWE)>0.5), regardless of whether we used the ROI as an inclusive mask or not. This suggests that valuation was only at play during the creative idea production of the FGAT-distant condition, as opposed to when subjects formed spontaneous associations during the FGAT-first condition.

Together, these analyses confirm our central hypothesis that the evaluation phase of creativity partly relies on the assignment of subjective values encoded in the BVS. In the following sections, we investigated how originality and adequacy of ideas were represented in the brain.

2.2.2. Originality and adequacy ratings are encoded in the DMN and the ECN during idea evaluation and production

Defining the functional localizer of originality and adequacy evaluation

To investigate the neural representation of adequacy and originality of ideas, we followed the same parametric modulation approach as before, this time with originality and adequacy ratings as parametric modulators. As participants rated originality and adequacy outside the scanner, we used the likeability rating task to create localizers of adequacy and originality judgements.

We found a significant correlation between the associations' originality ratings and the BOLD signal in regions classically identified as parts of the DMN during the likeability rating task (Figure 4A): the inferior frontal gyrus ([-44, 28, -4], t(37)=11.46, pFWE<10^{-16}), the middle temporal gyrus ([-56, -15, -12], t(37)=9.30, pFWE<10^{-16}), the dorsomedial prefrontal cortex ([-6, 48, 16], t(37)=9.10, pFWE=3.10^{-15}), the lateral orbitofrontal cortex ([39, 30, -10], t(37)=7.57, pFWE=3.10^{-8}), and the pre-supplementary motor area ([-4, 20, 58], t(37)=7.48, pFWE=6.10^{-7}).

In parallel, we found a significant correlation between the associations' adequacy ratings and the BOLD signal in regions classically identified as parts of the ECN during the likeability rating task (Figure 4A): the precuneus ([-6, -70, 38], t(37)=7.80, pFWE=3.10^{-11}), the left and right intraparietal lobule ([-41, -48, 38], t(37)=7.77, pFWE=1.10^{-16}; [44, -38, 43], t(37)=7.04, pFWE=9.10^{-9}), the posterior cingulate cortex ([-6, -25, 30], t(37)=7.59, pFWE=5.10^{-9}), the left and right lateral frontal pole ([-36, 52, 3], t(37)=7.36, pFWE=4.10^{-6}; [34, 62, 6], t(37)=6.24, pFWE=5.10^{-6}), and the inferior temporal sulcus ([-61, -30, -17], t(37)=6.50, pFWE=7.10^{-5} - see Table 1 for all significant clusters).
This aligns with our hypothesis that originality and adequacy ratings are encoded during idea evaluation, although we had no specific hypotheses regarding the respective underlying brain networks.

Comparing the functional localizer of originality and adequacy evaluation to atlas functional networks

To position the identified regions in brain networks and define ROI masks, we followed the same approach as for the likeability localizer (Figure 5). We found that the regions reflecting originality ratings mostly overlapped with the DMN (82 262 voxels out of 236 590, i.e. 35% of overlap) and that the regions reflecting adequacy ratings mostly overlapped with the ECN 59 921 voxels out of 150

112, i.e. 40% of overlap), more so than with the other 7 networks, which confirmed our visual observations (see Figure 5 and Table S1 for all overlaps). For the following analyses, we defined the DMN and ECN ROIs as the overlapping voxels between the functional localizer and its corresponding atlas functional network while excluding the voxels that were in common with the BVS ROI (the dark yellow and dark red areas in Figure 5). Figure 5 also mentions "ECN excluding BVS" and "DMN excluding BVS" as we removed the BVS regions overlapping with Yeo et al.'s (52) ECN and DMN from their respective ROIs in the following analyses to improve specificity.

Locating the neural encoding of originality and adequacy ratings during idea production

To investigate whether the DMN and ECN respectively represented originality and adequacy during the production of creative ideas, we followed the same approach as for likeability. We performed ROI-based parametric modulation analyses during the FGAT-distant to determine whether each network encoded its associated dimension during the production of creative ideas and specify which regions in particular.

We found a significant correlation with originality within the DMN ROI (set p-value=3.10^{-4}; see Table 2 for details). Plus, when investigating the clusters within the ROI, we found a significant correlation between the originality of the response and the BOLD signal in the medial frontal pole ([-11, 55, 0], t(37)=4.68, peak p-value(FWE)=0.044; Figure 4B).
For adequacy, the set p-value was not significant (p=0.29), and we found no significant correlation between the associations' adequacy and the BOLD signal anywhere at the cluster level. We resorted to using small-volume correction with a sphere centered on the five activation peaks from the localizer. We found a significant correlation between the associations' adequacy and the BOLD signal only in the sphere located in the lateral frontal pole (sphere center coordinates: [34, 62 6], peak activation coordinates: [39, 58, 0], t(37)=3.37, peak pFWE=0.045, set p-value=0.049; Figure 4B; see Table 2 for details).

Overall, these analyses first revealed that the DMN and the ECN respectively encoded originality and adequacy values during the likeability rating task, i.e. even when we had not instructed the participants to consider these two dimensions. In other words, participants tracked the association's originality and adequacy while rating how much they liked it. Second, this encoding in the DMN and ECN was found again during the creativity task, suggesting that creative production also involves an evaluation of originality and adequacy on top of likeability.

2.2.3. The contribution of the DMN and ECN to the BVS activity mirrors the contribution of originality and adequacy to the likeability ratings

Building on the encoding of originality and adequacy by the DMN and ECN, we tested whether the contribution of ECN and DMN activities to the BVS activity followed the same relationship as the contribution of adequacy and originality to likeability judgements (Figure S3). For each participant, we extracted the timeseries of activity during the FGAT-distant condition for each network. Then, we fitted the CES value function to the fMRI data, with the BVS timeseries as the dependent variable and DMN and ECN timeseries as the independent variables (Figure S3A). This allowed us to estimate a neural α parameter and a neural δ parameter. Across individuals, we found a significant correlation between the α_{neural} and $\alpha_{\text{behavioural}}$ parameters (r=0.39, p=0.023) but not between the δ parameters (r=0.02, p=0.9) (Figure S3B). Interestingly, when performing the same analysis with the timeseries extracted from the resting-state session conducted at the end of the experiment, we still found a significant correlation between the α_{neural} and α_{behavior} parameters (r=0.46, p=0.0049) and again, no

significant correlation for δ (r=-0.11, p=0.52) (Figure S3C). Together, these results suggest that the pattern of functional connectivity between the BVS, the ECN and the DMN reflects individual preferences, both during the creativity task and at rest.

3. Discussion

Summary of findings

In this study, we used a creative word association task and several rating tasks to reveal the implication and the neural substrates of subjective valuation during the production of creative ideas. Our behavioral results replicate our prior work by showing that the subjective value of an idea depends on its originality and adequacy. We also replicate that valuation varies across individuals, resulting in the identification of individual patterns that relate to creative abilities. At the neural level, we show that i) subjective valuation is supported by the BVS during creative idea production; ii) originality and adequacy evaluations are respectively represented in the DMN and the ECN during creative idea production and iii) the DMN and ECN contribute to the BVS activity in a fashion that mirrors behavioral preferences and supports individual variability.
These results reveal the underlying neurocognitive mechanisms of the evaluation step of creativity and validate our hypothesis that individual preferences play a role in creativity.

The role of the BVS in valuation and decision-making

We showed that the subjective value of an idea is represented in individuals' BVS when we explicitly asked them to rate how much they liked an idea, but also when they focused on producing a creative idea.

This central result is consistent with two BVS properties reported in decision-making literature (34). First, the involvement of the BVS in the valuation of creative ideas is consistent with its generic property: some have demonstrated that the BVS could reflect the subjective value of different kinds of items, no matter their nature (36). This property aligns with the neural common currency framework, which states that the values of different and disparate types of items can be represented in the same brain regions and allows for their comparison (37). Second, the valuation of ideas in the BVS during creative production is consistent with the automatic property of the network: the BVS can reflect an item's value even when an individual is not explicitly instructed to rate how much they like it. Even when an individual is focused on another task, for instance, when passively viewing a stimulus (38), when determining a person's age (34,36) - or in our case, when producing a creative word association - the BVS still reflects how much individuals like the item they are processing.

In parallel, the role of the BVS - and, in particular, the ventromedial prefrontal cortex (vmPFC) - has been challenged by recent studies. They argue that rather than representing one's subjective value for the object they are processing (33,34,36), the BVS could be representing slightly different variables, such as one's goal value (53–56) or one's confidence in the rating (57,58). In the current study, control analyses found no significant evidence indicating a confound with confidence. On the other hand, our study design does not allow us to differentiate between subjective and goal values. Subjective value differs from goal value in that the former is generally stable, regardless of the context, while the latter highly depends on one's current goal. For example, the subjective value of a boat might always be minimal for someone not interested in traveling on the sea, but its goal value would increase dramatically if that person were stranded on a desert island.

This distinction might be relevant to the current study, where we observe that likeability ratings are represented in the BVS during the "distant" condition of the FGAT (where we instructed participants to give a creative association) but not during the "first" condition (where we instructed participants to

give the first association that came to their mind). Notably, during the likeability rating task, the instruction was to rate the associations in the context of the FGAT-distant condition (where the goal was to be creative). As a result, the ratings given by the participants may reflect goal values more than subjective values. If so, since the goal to think creatively is similar in the FGAT-distant condition and the likeability rating task, the goal value would remain the same, which might explain why we observed its encoding in the BVS. In contrast, the goal in the FGAT-first condition does not involve creativity and thus differs from that of the likeability rating task. This could explain our null result regarding the correlation between the brain activity during the FGAT-first and the likeability ratings, as these would reflect the goal value for a goal that has yet to be established.

Some studies also linked the BVS to the encoding of yet other dimensions. They observed that novelty processing was related to increased activity within the ventral striatum (59), the substantia nigra and the ventral tegmental area (59–61). This heightened activity was viewed as a signal for learning when it was associated with enhanced synaptic plasticity in the hippocampus (62). However, these studies did not assess the relationship between BVS and novelty processing with creative functions.

The role of the BVS in creativity

Despite the widely acknowledged impact of motivation on creativity, the role of the BVS has been largely overlooked, with only a few studies debating its involvement in creativity, mainly for originality or adequacy processing. Huang et al. (42) showed that, during creative evaluation, BVS regions, such as the caudate nucleus and the substantia nigra, represented originality. In a later study, however, they showed that other regions from the BVS, namely the ventral striatum and orbitofrontal cortex, actually represented adequacy (29). Similarly, Matheson et al. (25) found that medial prefrontal cortex (mPFC) regions which belong to both the BVS and the DMN supported adequacy processing. Additionally, functional connectivity in subcortical regions of the BVS, such as the putamen (63) and grey matter volumes in the striatum and ventral tegmental area (41,43) were all related to better divergent thinking abilities.

The involvement of the BVS in creativity is corroborated by investigations at the molecular level. Several studies have highlighted that dopaminergic modulation of frontostriatal networks could support creative cognition: the release of dopamine in the striatum could enhance creativity by enabling cognitive flexibility, and in the prefrontal cortex, dopaminergic modulation could help with the need for persistence in creativity (45,47). Another study showed an inverted U-shape effect of dopamine on creativity, which builds on the notion that creative abilities rely on an optimal trade-off level of dopamine (46). However, this study's proxy for subcortical dopaminergic function (the eye blink rate) does not differentiate between the different dopamine pathways and receptors. Similarly, Aberg et al. (44) showed that individuals with decreased dopamine in the right hemisphere scored better in creativity tasks requiring remote associations (Alternative Uses Task and Remote Associates Test).

An overarching complication when studying motivation and creativity is the anatomical similarity between the BVS and the DMN. In the current study, we assessed the overlap of the DMN (as defined by Yeo and colleagues' seven networks atlas (52)) and the BVS (as defined by the "reward" term-based meta-analysis of the Neurosynth platform, https://neurosynth.org/) and quantified a total of 17 530 voxels, a volume which amounts to 7% of the DMN, or 14% BVS (Supplementary Table 1). This anatomical similarity can be a common issue in the literature where some creativity studies label

"DMN" regions that would be labeled "BVS" by neuroeconomists. It will be critical for future research to be aware of this overlap and eliminate this source of confusion, for instance, by using localizers, as we did in the current study.

Regardless, while the literature does not clearly establish how the BVS and its related dopaminergic pathways are involved in creativity, it converges towards confirming their central role (44,64). Nevertheless, the present study empirically demonstrates the involvement of the BVS in encoding an idea's subjective value during idea evaluation and production. Previous findings linking the BVS with originality or adequacy processing may only be due to the correlation of likeability with these two dimensions. In contrast, our innovative design helps break down idea evaluation into the monitoring of ideas' originality and adequacy and the valuation of ideas, clarifying the specific role of the BVS in this process. We also challenge the established roles of the DMN and ECN by investigating the encoding of originality and adequacy, whose neural correlates remain unclear.

The roles of the DMN and ECN in creativity: revisiting the classical generative and evaluative distinction

The current literature broadly establishes that the DMN is involved in the generation phase of creativity in a spontaneous manner that helps form new associations. In parallel, the ECN is reported to support idea evaluation and selection in a goal-directed and controlled manner. This one-to-one matching of the dual process of creativity to a dual-network organization is supported by many studies suggesting that the DMN is involved in idea generation (16,23–27); that the ECN is involved in idea evaluation (16,23–26,29,30); and that creativity relies on these networks' cooperation (5,11,32,65).

However, some findings challenge the exact mapping of the two-fold view of creativity to its dual neural basis. First, several studies, like ours, report that idea evaluation can be partly supported by the DMN (10,23,23,24). Some, even more in alignment with our results, precise that the DMN is related to originality processing (25,26,30). If we consider that achieving originality requires making new associations, it makes sense that the DMN, which has consistently been associated with associative processes during generation, would encode this dimension during evaluation. However, other studies slightly diverge from our own and find that the DMN supports the processing of adequacy (42). Despite some diverging results that could be due to tasks and analysis differences - many studies challenge the now common conception that the DMN is only involved in idea generation. Second, other studies, like ours, find that the involvement of the ECN is indeed related to the evaluation of an idea, particularly its adequacy dimension (25,30). If we consider that achieving adequacy requires exploring candidate ideas and sorting through them to find the most adequate one, it makes sense for this to be associated with cognitive control processes and, therefore, supported by the ECN. However, contrary to our results, others find that the ECN supports the evaluation of an idea's originality (25,26,29).

In summary, although the studies cited above lack perfect convergence, they question the neural bases of the dual process model of creativity and suggest that evaluation (as in our study) processes rely on both the DMN and ECN.

The complementary roles of the BVS, the DMN and the ECN in creativity

Beyond their brain location, more and more studies question the computations at play during creativity, particularly its evaluation phase (11,18,29). They highlight that this step is often simplified

and overlooks the importance of emotions, motivation or valuation. Based on Huang et al.'s (29) results, which showed that originality and adequacy processing relied respectively on regions of the ECN and the BVS, Kleinmintz et al. (11) attempted to dissociate evaluation into "monitoring" and "valuation" subprocesses. They propose that the assessment of originality requires cognitive control akin to monitoring and that, in contrast, the assessment of adequacy is linked to emotional and motivational processes akin to valuation.

Our view partly differs from theirs. First, we dissociate evaluation into monitoring and valuation as well but align monitoring with the evaluation of adequacy and originality (i.e., the monitoring of the dimensions necessary for a creative goal) and valuation with the assignment of a subjective value that combines the monitored adequacy and originality.
Second, we show that the ECN encodes adequacy, not originality and that the DMN encodes originality. Finally and most importantly, we show that the BVS underlies the valuation of ideas, not the processing of adequacy. These diverging results may stem from variations in task design: in the study conducted by Huang et al. (29), participants reviewed creative solutions to riddles and assessed whether they were adequate or not, while here, participants reviewed creative word associations and assessed how much they liked them, and how adequate and original they were. Additionally, methodological differences might contribute to divergences in results: Huang et al. (29) used high versus low adequacy and originality contrasts, while we used parametric modulation based on adequacy and originality ratings. Overall, we agree with Kleinmintz et al. (11) that what is commonly labeled evaluation should be subdivided into monitoring and valuation subprocesses. We propose an alternative model in which originality and adequacy are monitored and integrated during valuation, which then guides the final selection step during idea production.

A remaining important question is whether evaluation's monitoring and valuation subcomponents are consistently both at play during creativity. In the current study, we show that both valuation and monitoring of originality and adequacy are at play during the production of creative word associations: it would be interesting to generalize these results to other creativity tasks. This would require creativity studies to include likeability rating tasks in their design to assess the participants' subjective values and check if they correlate with behavioral and neural variables (such as the response times and the BVS activity used in the current study).

Notably, the current study finds that subjective value scales with originality and adequacy ratings. First, this result means that valuation builds on the two significant dimensions of creativity. Second, it adds to prior research on multi-attribute value-based decision-making. This literature studies choices that depend on the value of several criteria; for example, food choices can depend on taste and health attributes. However, the brain networks implicated in multi-attribute value-based decision-making are still unclear. Indeed, the neural representation of attributes may be contingent upon their nature, and in some cases, attributes may not be represented at all in the brain. For instance, in the context of food choices, regions such as the dorsolateral prefrontal cortex (dlPFC) are associated with the healthy attributes of food, while the ventromedial prefrontal cortex (vmPFC) is linked to the tasty attributes (66). Yet, the neural representation remains uncertain for risky choices and perceptual attributes like shape or colors, with some evidence for attribute representation in the dlPFC and combined value representation in the vmPFC (67). Several studies do not report specific activity directly linked to attributes, while some suggest that attributes are represented in the same areas as the combined value (68). Certain studies, such as the one by Hunt et al. (69), have focused on comparing attributes in the intraparietal lobule, while others propose the involvement of the dlPFC, a component of the ECN, in attribute representation and comparison (70). It is essential to highlight that these studies often report

brain activities in specific regions rather than brain networks, making direct comparisons challenging. For example, the mPFC is part of the DMN, but it also substantially overlaps with the social network. Here, we find that during creative valuation, the attributes of creative ideas (originality and adequacy) are separately represented in networks consistently reported in creativity research (in the DMN and ECN, respectively). These findings illustrate that attributes can be represented in different brain regions and that these regions (here, creativity networks) could be relevant to the specific nature of the attributes under consideration (here, creative dimensions).

Finally, the significant correlation between the neural task-related parameter associated with DMN and ECN activities (αneural) and the behavioral parameters related to originality and adequacy assessments (αbehavioral) suggests a neural basis for individual preferences in creativity. The persistence of this correlation during a resting-state session highlights the enduring connectivity of these neural networks. These findings underscore the dynamic interplay between cognitive networks involved in creativity and subjective valuation, offering valuable insights into the neural underpinnings of preferences and decision-making in creativity.

The link between idea valuation and creative abilities

The present study not only shows that individuals combine the dimensions of originality and adequacy into a subjective value, but it also demonstrates that the way they combine them (as estimated by the α and δ parameters of the CES model) relates to their creative abilities: giving more weight to an idea's originality over its adequacy (i.e., having a high α) and preferring a trade-off of these two dimensions rather than an extreme of either (i.e., having a low δ) correlated with higher scores in creativity tests.

This finding replicates Lopez-Persem et al. (19) and suggests, together with other studies, that the evaluation step is essential in the creative process. For instance, previous results showed that an overly stringent evaluation inhibited creativity (26,71). It was also illustrated by Kleinmintz et al.'s study (72), in which they found that improviser musicians were more lenient than non-improviser musicians when rating creative ideas and that this helped them achieve better creativity.

In parallel, Diedrich et al. (73) showed that scores in a creativity task were correlated to the idea's originality and not to its adequacy. Adequacy did predict creativity but only in very original ideas, as the interaction of originality and adequacy explained additional variance of the creativity scores. Here, we computationally quantify similar effects with the α and δ parameters: creativity is linked to giving greater importance to originality (high α) but still preferring a trade-off of originality and adequacy over extremely original but poorly adequate options (low δ).

Limitations and perspectives

The present study identifies that likeability, originality and adequacy are respectively encoded in the BVS, DMN and ECN as part of an evaluation process, both during a rating task and a creative production task. However, these interpretations are based on parametric modulation analyses, which strictly indicate brain regions where the BOLD signal increases as a function of a given factor (the parametric modulator) that varies across trials. Instead of concluding that "the likeability of ideas is encoded in the BVS during the rating task", a more conservative interpretation would be "the greater the likeability rating, the greater the BOLD signal in regions of the BVS". We can thus not exclude that another variable might mediate these correlations.

In other studies, higher activity in the BVS during evaluation was interpreted as emotional arousal (42) or motivation (23). Additionally, Wu et al. (30) proposed that higher activity in the DMN during evaluation may stem from participants generating alternatives while viewing the one in front of them. Our analyses cannot rule out these alternative explanations. For instance, generating original ideas might require more activity in the DMN without necessarily implying the DMN's direct involvement in the evaluation step of creativity. However, the fact that this pattern also emerged in the rating task strongly supports the latter possibility.

In conclusion, the current study clarifies some cognitive and neural mechanisms involved in idea evaluation, a critical but long-overlooked step of the creative process. By combining creativity and neuroeconomics methods, this study shows that valuation participates in idea evaluation, meaning that individual preferences influence the creative process. These preferences depend on a trade-off of originality and adequacy, which are primary creativity criteria. At the neural level, the results of this study add the BVS to the main creativity networks classically reported, the ECN and DMN.
Future research should focus on how these three networks interact during idea evaluation. In parallel, to delve deeper into the decision-making processes of creativity, it would be helpful to investigate the selection step of creativity, i.e., how individuals choose the best candidate idea. Like monetary or food choices, creative choices are likely driven by subjective values, as Lopez-Persem et al. (19) suggested. This also paves the way for investigating suboptimal or biased choices, which are a central issue considering the growing literature on cognitive biases in creativity research (71,74,75).

4. Material and Methods

4.1. Participants

An official ethics committee approved the study (CPP Ouest II – Angers). We recruited and tested forty participants at the CENIR platform of the Paris Brain Institute (ICM). All participants were French native speakers, right-handed, with correct or corrected vision, and no neurological or psychological disease history. We excluded two participants from analyses, one because we interrupted MRI scanning after they suffered from a claustrophobic episode and one because of a technical issue during MRI scanning. The final sample comprised thirty-eight participants (19 women, age = 26.5 ±4.0 (M±SEM), level of education = 16.5 ±1.9 years (M±SEM)). They were paid 110€ for a four-hour testing session that included MRI scanning and cognitive and creativity tests inside and outside the scanner.

4.2 Experimental design

After giving informed consent, participants completed an MRI session composed of an anatomical T1 scan, three task-based fMRI scans while performing an FGAT, a rating task and a choice task, and a resting-state fMRI scan. Participants then completed an extra rating task and a battery of creativity tests outside the MRI. We used Matlab (MATLAB. (2020). 9.9.0.1495850 (R2020b). Natick, 624 Massachusetts: The MathWorks Inc.) to program the tasks and the Qualtrics software (Qualtrics, Provo, UT, USA. https://www.qualtrics.com) to implement creativity tests.

4.2.1. Free Generation of Association Task

In the Free Generation of Association Task (Figure 1B), which is reported to capture critical aspects of creativity, participants generate creative word associations (76). In our experimental design, the task comprised two successive conditions, each comprising 5 training trials and 62 randomized test trials. Each trial displayed a fixation cross for 1.6 to 3.2 seconds, jittered with a uniform distribution. Then, a cue word was displayed. In the "first" condition, participants had up to 10 seconds to give the first word that came to mind after reading the cue word (for example, participants might answer “father” to the cue word “mother”). In the "distant" condition, they had up to 20 seconds to provide a distant word, so the cue and response words would result in a creative word association (for example, participants might answer “nature” to the cue word “mother”). Participants pressed the response button with their right index finger when they had an answer in mind. Then, they said the response word out loud into a microphone. The experimenter typed the response and displayed it on the participant screen. Participants then had the opportunity to repeat their response in case the experimenter had misheard (by pressing the response button again with their right index finger) or to validate the response (by pressing the validation button with their right ring finger). The exact instructions given to the participants are in the *Supplementary Methods*.

4.2.2. Rating task

Selection of the associations for the rating tasks

We split the rating task in two (a likeability rating task performed inside the scanner and an originality and adequacy rating task performed outside the scanner). Each rating task counted five training trials and a variable number of test trials (M±SEM=145±2), depending on the validity of their FGAT answers.

Validity of the FGAT associations

Not all FGAT-first and FGAT-distant associations were selected for the rating tasks, only the associations that followed these criteria were selected (i) the first three letters of the FGAT-first and FGAT-distant responses to the cue word must be different, (ii) one of the responses must not contain the other (e.g. 'count' and 'accountant' have the word 'count' in common and would not respect this criterion), (iii) the FGAT-first and FGAT-distant responses to one cue word must be comparable in length (no more than five letters of difference) and (iv) the FGAT-distant response must not be too long (no more than nine letters)

Then, we randomly selected one-fifth of the accepted cue words and paired them with five other responses that the participant had not generated: four of those from a different study's dataset, including (i) a highly frequent FGAT-first response, (ii) a highly infrequent FGAT-first response, (iii) a highly frequent FGAT-distant response and (iv) a highly infrequent FGAT-distant response. The fifth response was an unrelated word (for example, the cue word 'cow' was associated with the unrelated response 'inverse'). Overall, this added up to a maximum of 186 rating trials (less if the 124 FGAT-first and FGAT-distant associations did not all follow the four criteria mentioned above), selected for their diversity and randomized before the start of the task.

Overall, for both rating tasks, the trials were composed of the following: 66% of the trials were evenly made up of the participant's valid FGAT-first and FGAT-distant associations; 27% of the trials were a sample of frequent and rare responses taken from another study using the same FGAT cue words; and finally 7% of the trials were associations of unrelated words. We added these associations to cover a wide range of adequacy and originality ratings, ensuring a robust estimation of likeability with sufficient statistical power.

Likeability rating task

The first rating task, i.e. the likeability rating task (Figure 1C), was performed in the MRI scanner. Participants had to indicate how much they liked the association or how satisfying it was in the context of the FGAT-distant condition. In this task, each trial started with a fixation cross displayed for 1.6 to 3.2 seconds (display times were determined by a random jitter with a uniform distribution). Then, a cue word (for example, "mother") was displayed alone for 0 to 0.5 seconds (display times were determined by a random jitter with a uniform distribution). Then, a response appeared under the cue word. This association (for example, "mother-nature") remained alone for 1.6 to 3.2 seconds (display times were determined by a random jitter with a uniform distribution). Then, a rating scale appeared below the association. The rating scale's low to high values were represented from left to right, with the words "not at all" and "very much" located at the extremities but without any numerical values. A segment indicated the middle of the scale, which was divided into 101 hidden steps, later converted into ratings ranging between 0 and 100. We displayed a heart icon (for likeability) under the rating scale. To provide a rating, participants had to move a cursor by pressing the first and second MRI response buttons with the right index and right middle finger and then validate the rating by pressing the third button with their right ring finger. Once the response was validated, the subsequent trial began. The exact instructions given to the participants are in the *Supplementary Methods*.

Originality and adequacy rating task

The second rating task, i.e. the originality and adequacy rating task (Figure 1D), was completed after the choice task and outside the MRI. Again, each trial displayed a two-word association (for example, "mother-nature") and asked participants to subsequently rate how original and how adequate it was.

The order of originality and adequacy ratings was counterbalanced across trials. Each trial started with the screen displaying a cue word. After 0.3 seconds, a response word appeared under the cue, and after 0.4 seconds, a scale appeared under the two-word association. The scale was similar to the likeability rating scale except for the icon displayed underneath: a star for originality and a target and arrow for adequacy. Participants rated the association by moving the slider across the scale using the left and right arrows of the keyboard and validated by pressing the spacebar. Then, a new scale appeared underneath the same association, indicating the second dimension (adequacy or originality). Participants provided their ratings similarly and then started the subsequent trial.
We told participants to use the whole scale throughout the task. No time limit was applied, but the instruction was to respond spontaneously. The exact instructions given to the participants are in the *Supplementary Methods*.

4.2.3. Choice task

The choice task was performed in the MRI and comprised five training trials and an average of 187 randomized test trials (the exact number varied between participants depending on the variability of their FGAT answers and ratings). Each trial displayed two possible responses to an FGAT cue, with the cue word on the top of the screen and the two response options words below, on the same horizontal line (for example, “mother” was displayed on top of "nature" and "father"). Participants had to choose which of the two responses would result in the best association with the top cue in the FGAT-distant condition. No time limit was applied, but the instruction was to respond spontaneously. Note that the results of this task go beyond the scope of this paper and will instead be the focus of a future publication. The exact instructions given to the participants are in the *Supplementary Methods*.

4.2.4. Battery of creativity tests

The battery comprised a daily-life creativity questionnaire, self-reports, and established creativity tasks belonging to three main frameworks of creativity - the divergent thinking approach, the associative theory, and the insight problem-solving approach.

Inventory of Creative Activities and Achievements: the inventory of creative activities and achievements was first designed by Diedrich et al. (77) as an ecological measure of creativity. It focuses on eight domains of creativity (literature, music, crafts, cooking, sports, visual arts, performing arts, and science and engineering). For each domain, participants reported their level and their frequency of engagement over the past ten years. They also specified their level of creative accomplishment in each of these domains.
Scoring: we computed the ICAA score as the mean of the creative activities score (C-act) and the creative achievements score (C-ach). First, for the creative activities score (C-act), we summed the frequency at which the participant had engaged in each of the eight creativity domains using an ordinal scale ranging from 0 (never) to 4 (more than ten times). Then, for the creative achievements score (C-ach), we summed the participants' levels in each of the eight creativity domains. These ranged from 0 (“never engaged in this domain”) to 10 (“I have already sold some of my work in this domain”).

Drawing task: the drawing task (78) comprised a training trial and 12 test trials. We instructed participants to include incomplete shapes in creative drawings. The 12 incomplete shapes were relatively similar: they were all composed of 4 lines, either straight, curved or right-angled, and exhibited horizontal symmetry (cf. (78) for an example). Participants completed the 12 drawings at their own pace. Then, they reviewed each drawing and gave each one a verbal title.

Scoring: We followed the consensual assessment technique that is advised for scoring such a creativity task (79). We designated four judges from the lab who were familiar with creativity judgments but had not seen the data before the rating. For each of the twelve shapes, the judges first saw the incomplete shape, then each participant's drawing using that shape, in a blind and randomized order. Then, the judges gave each drawing a rating between 0 (not creative at all) and 4 (extremely creative). We tested the inter-judge independent rating consistency using an intraclass correlation analysis, which gives the mean correlation between the judges' ratings ($r=0.8239 \pm 0.02$; M±SEM).

Combination of associates task: Bendetowicz et al. (80) first developed the combination of associates task by adapting the remote associative task from Mednick (81). After five training trials, participants performed 40 randomized test trials, each displaying three cue words with no apparent association: they had to find a fourth word that linked all of them (for example, the link between "map", "dig", and "discover" is "treasure").
Scoring: The CAT score used for the analyses was the participants' total number of accurate answers.

Associative fluency task: in this task, adapted from Benedek et al. (82), participants had two minutes to type as many words related to a cue word as possible. We chose this associative design over simple category or letter fluency tasks to measure creative abilities on top of fluency. We selected six cue words ("garden", "wine", "rock", "opinion", "call", and "finger") among the FGAT cues for their diversity in steepness. The steepness is the ratio of the frequency of the most frequent answer over the frequency of the second most frequent answer: a steep cue word (e.g., "cat") has a very common first associate ("dog"); a flat cue word has several equally-common first associates. We measured typing speed and accounted for it in the fluency analysis.
Scoring: The score used for the analyses was the total number of answers given to a cue word, averaged across all cue words.

Participants also performed an alternative uses task (AUT), a self-report of their creativity level (i.e. "How creative are you on a scale of 1 to 100?") and a questionnaire regarding their preferences in creativity (e.g., "Would you prefer an idea to be useful or novel?") that were not analyzed or used in this paper but will be part of future papers.

4.3. Statistical analyses of the behavior

We performed all the analyses using Matlab (MATLAB. (2022). 9.12.0.2009381 (R2022a). Natick, Massachusetts: The MathWorks Inc.).

4.3.1. Differences in originality, adequacy and frequency between FGAT-first and FGAT-distant responses

For each individual, we computed the mean of originality and adequacy ratings separately for items of the FGAT-first and FGAT-distant conditions. Then, we compared the difference in adequacy between the two tasks to their difference in originality using a paired two-tailed t-test at the group level. We computed the frequency of association of all FGAT responses using the French database Dictaverf (http://dictaverf.nsu.ru/) (83). This database is built on spontaneous associations provided by at least 400 individuals in response to 1081 words (each person saw 100 random words). Frequencies were log-transformed to take into account their skewed distribution toward 0. We compared the frequency of the FGAT-first responses and the FGAT-distant responses at the group level using a paired two-tailed t-test.

4.3.2. Relationship between FGAT response times and likeability ratings

We defined participants' response times in the FGAT as the time between the cue display and the participants' first button press, which indicated they had an answer in mind. Then, at the individual level, we performed a linear regression of response times against likeability ratings, standardized between participants. We did two distinct regressions for the FGAT-first and FGAT-distant conditions. At the group level, we performed a one-sample, two-tailed t-test to test the significativity of the effect of likeability on response times. We also tested the difference in the effect of likeability on response times (regression coefficients) between the two FGAT conditions using a paired two-tailed t-test on the regression coefficients. Note that all variables were standardized at the subject level, and non-standardized data are depicted in figures.

We performed a control analysis to compare the effects of likeability and confidence on response times. We did a GLM on response times at the individual level, where we used likeability ratings and squared likeability ratings (a proxy for confidence) as regressors. We standardized response times and likeability ratings between participants. We compared the effects of likeability ratings and squared likeability ratings at the group level using a paired two-tailed t-test.

4.3.3. Relationship between likeability, originality and adequacy

We fitted the participants' data at the individual level with the Constant Elasticity of Substitution utility function (50,51), which provided the best fit in our previous study using the same experimental design (19):

$$Likeability\ rating_i = (\alpha \times Originality\ rating_i^{\delta} + (1 - \alpha) Adequacy\ rating_i^{\delta})^{\frac{1}{\delta}}$$

"i" stands for one association, α stands for the weight given to originality ratings, and δ stands for the preference for extremes in originality or adequacy as opposed to a trade-off of those dimensions.
We used the Matlab VBA toolbox (https://mbb-team.github.io/VBA-toolbox/), which implements Variational Bayesian analysis under the Laplace approximation (84) to fit the model to individual data and estimate individual parameters. We tested for significance the estimated parameters of the CES model at the group level using paired two-tailed t-tests against their prior values (0.5 for α and 1 for δ).

4.3.4. Post-hoc analyses on the alpha parameter and the relationship between likeability and frequency

Next, we performed post-hoc analyses on the α parameter of the CES, which captures the weight of originality relative to adequacy in the likeability ratings. First, we computed the coefficient of variation: α's standard deviation (SD=0.266) divided by its mean value (M=0.46).
In parallel, we performed a linear regression of likeability against frequency at the individual level on standardized values. We tested its significativity at the group level using a one-sample, two-tailed t-test. Then, we tested the group-level correlation between the α parameter and the slope of the likeability-frequency linear regression.

4.3.5. Creative abilities analyses and canonical correlation

We pooled the scores for the associative fluency task, the Combination of Associates Task (CAT), the drawing task and the Inventory of Creative Activities and Achievements (ICAA) into a "creativity scores" set and the α and δ parameters of the evaluation model into an "evaluation parameters" set. Then, we performed a canonical correlation analysis of these two sets. Canonical correlation analysis identifies the shared variance between two datasets, summarizing it as canonical variables. They are organized based on the strength of correlations between the two datasets. Here, we examined the correlation between the canonical variables in each dataset and presented their loading coefficients, i.e. the contributions of each creativity score and each evaluation parameter to their respective canonical variable. Correlation coefficients were tested for significance using Bartlett's modified chi-squared tests of the Matlab "canoncorr" function, and loading coefficients were tested for significance using the two-tailed t-test of the Matlab "corr" function.

4.4. MRI data acquisition and preprocessing

4.4.1. Scanning parameters

We acquired neuroimaging data on a 3T MRI scanner (Siemens 3T Magnetom Prisma Fit) with a 64-channel head coil.
Four functional runs were acquired over the four tasks (FGAT-first, FGAT-distant, likeability rating task, choice task) using multi-echo echo-planar imaging (EPI) sequences. The number of whole-brain volumes per run varied between tasks but also between participants since all tasks were self-paced (mean, [min; max]: FGAT-first= 379, [317;454], FGAT-distant: 612, [359;856]; likeability rating task: 800, [650;1012] and choice task: 662, [525;821]). We did not record any dummy scans and, therefore, did not discard any volume. The functional runs used the following parameters: repetition time (TR) = 1660 ms; echo times (TE) for echo 1 = 14.2 ms, echo 2 = 35.39 ms, and echo 3 = 56.58 ms; flip angle = 74°; 60 slices, slice thickness = 2.50 mm; isotropic voxel size of 2.5 mm; Ipat acceleration factor = 2; multiband = 3; and interleaved slice ordering.
After the EPI acquisitions, we acquired a T1-weighted structural image with the following parameters: TR = 2300 ms, TE = 2.76 ms, flip angle = 9°, 192 sagittal slices with a 1-mm thickness, isotropic voxel size of 1 mm, Ipat acceleration factor = 2.
Finally, we added a resting-state fMRI session of 10 min (360 volumes) with the same acquisition parameters as the task runs.

4.4.2. Preprocessing

We performed the preprocessing of the on-task fMRI data separately for each run and the resting-state data using the afni_proc.py pipeline from the Analysis of Functional Neuroimages software (AFNI; https://afni.nimh.nih.gov). The different preprocessing steps of the data included slice timing correction and realignment to the first volume (computed on the first echo). We then combined the preprocessed data using the TE-dependent analysis of multi-echo fMRI data (TEDANA; https://tedana.readthedocs.io/), version 0.0.9a1 (85). We co-registered the resulting data on the T1-weighted structural image using the Statistical Parametric Mapping (SPM) 12 package running in MATLAB (MATLAB R2017b, The MathWorks Inc., USA). We normalized the data to the Montreal Neurological Institute template brain using the transformation matrix computed from the normalization of the T1-weighted structural image with the default settings of the computational anatomy toolbox (CAT 12; http://dbm.neuro.uni-jena.de/cat/) (86) implemented in SPM 12.

4.5. Statistical analyses the fMRI

4.5.1. Parametric modulation analyses

We entered the resulting normalized data from the task-based fMRI in general linear models in SPM. In this analysis, we entered 24 motion parameters and 42 physiological noise parameters as confounds regressed from the BOLD signal. In this preprocessing analysis, we used the Matlab PhysIO Toolbox (version 5.1.2, open-source code available as part of the TAPAS software collection: https://www.translationalneuromodeling.org/tapas (87)) to generate nuisance regressors for the GLM. The regressors were composed of (i) physiological (cardiac pulse and respiration) recordings used to generate RETROICOR (88) regressors, (ii) White Matter (WM) and CerebroSpinal Fluid (CSF) masks from the anatomical segmentation were used to extract components from compartments of non-interest using Principal Component Analysis (PCA) and (iii) motion parameters, composed of standard motion parameters, first temporal derivatives, standard motion parameters squared, and first temporal derivatives squared. Outlier volumes were eliminated when the Framewise Displacement (FD) exceeded 0.5mm.
Then, we used GLMs to explain pre-processed time-series at the individual level.

Modelling the neural encoding of likeability during idea evaluation (functional localizer): We applied the first, second and third models (GLM1, GLM2 and GLM3) to the likeability rating task. They all included a boxcar function capturing the signal between the cue display and the first button press to move the rating scale slider (one event per trial). GLM1's parametric modulator was the likeability rating of the response, while GLM2 and GLM3 were parametrically modulated by the originality and adequacy ratings, respectively. Note that GLM2 and GLM3 parametric modulators (originality and adequacy ratings, respectively) were not orthogonalized for the other dimension (meaning adequacy and originality, respectively), but control analyses with orthogonalization led to similar results.

Modelling the neural encoding of likeability during idea production: The fourth, fifth and sixth models (GLM4, GLM5 and GLM6) were similar to the first three models, except that we applied them to the FGAT-distant. They all included a boxcar function capturing the signal between the cue display and the first button press, signaling that the participant had found a response to the cue (one event per trial). GLM4's parametric modular was the likeability rating of the response, while GLM5's and GLM6's were the originality and adequacy ratings, respectively. Note that not all 62 FGAT-distant trials were included in this analysis: depending on the participant, the number of trials ranged between 34 and 59, as some associations had not been rated after controlling for FGAT-first and FGAT-distant similarity (see *Material & Methods 4.2.2. Rating task* for more details).

We convolved the regressors for all models with a canonical hemodynamic response function. The resulting masks were identified in statistical parametric maps (SPMs) at a threshold of $p < 0.05$, controlling for family-wise errors (FWE) at the cluster level. For GLMs 1 to 3, we found significant clusters at the whole brain level. For GLMs 4 and 5, we found significant clusters using small volume correction (SVC) with the overlap of the localizer and the networks of interest. For GLM6, SVC were spheres centered on the peak activation sites from the results of GLM3.

4.5.2. Functional localizers' similarity with networks of interest

To compare our resulting maps to our networks of interest, namely the BVS, the DMN and the ECN, we quantified the number of overlapping voxels between the SPMs of GLMs 1 to 3 and each of Yeo et al. (52) 7 intrinsic functional networks in the MNI152 referential. Since Yeo's atlas does not include

the BVS, we used the term-based meta-analysis of the Neurosynth platform (https://neurosynth.org/): the "atlas BVS network" is therefore the result of an automated meta-analysis of all studies in the Neurosynth database whose abstracts include the term "reward" at least once.
Before quantifying the overlaps, we verified that the atlas masks aligned with our results using the SPM checkReg function and applied it to our data with the ImCalc tool in SPM12.

4.5.3. Fitting the CES to the FGAT-distant and resting-state timeseries

To investigate the interaction between the BVS, ECN and DMN during the FGAT-distant, we employed a procedure previously used in the lab (14). To covary out the task-related signal from the FGAT distant run, we entered the preprocessed fMRI data in a GLM in SPM. We regressed out the onsets of each task-related event (cross onset, cue onset, first press event, validation event) from the BOLD signal. We then standardized and detrended the residuals of the GLM and concatenated them to obtain timeseries for each voxel. Timeseries for all voxels belonging to each network were averaged across voxels. Timeseries from the DMN and ECN were orthogonalized to remove shared variance between them. Using the VBA toolbox, we then fitted the following equation: $BVS_{FGAT\text{-}distant} = (\alpha DMN_{FGAT\text{-}distant}^{\delta} + (1\text{-}\alpha)ECN_{FGAT\text{-}distant}^{\delta})^{1/\delta}$

The estimated parameters from this equation will be referred to as the FGAT-distant α_{neural}, capturing the relative contribution of DMN and ECN activities to the BVS activity during the FGAT-distant, and the FGAT-distant δ_{neural}, capturing the curvature of contribution of the DMN and ECN activities to the BVS activity.

We preprocessed the resting-state BOLD signal in the same way as the task BOLD activity and extracted the timeseries from each network to apply the same analysis and fit the following equation: $BVS_{RS} = (\alpha DMN_{RS}^{\delta} + (1\text{-}\alpha)ECN_{RS}^{\delta})^{1/\delta}$

The estimated parameters from this equation will be referred to as the resting-state α_{neural} and the resting-state δ_{neural}.

We then used Pearson correlations to compare each neural parameter, estimated with the timeseries, to its respective behavioral parameter, estimated with the ratings.

References

1. Runco, M. A., & Jaeger, G. J. (2012). The Standard Definition of Creativity. Creativity Research Journal, 24(1), 92-96. https://doi.org/10.1080/10400419.2012.650092

2. Green, A. E., Beaty, R. E., Kenett, Y. N., & Kaufman, J. C. (2023). The Process Definition of Creativity. Creativity Research Journal, 0(0), 1-29. https://doi.org/10.1080/10400419.2023.2254573

3. Lloyd-Cox, J., Pickering, A., & Bhattacharya, J. (2022). Evaluating Creativity : How Idea Context and Rater Personality Affect Considerations of Novelty and Usefulness. Creativity Research Journal, 34(4), 373-390. https://doi.org/10.1080/10400419.2022.2125721

4. Silvia, P. J. (2008). Discernment and creativity : How well can people identify their most creative ideas? Psychology of Aesthetics, Creativity, and the Arts, 2(3), 139-146. https://doi.org/10.1037/1931-3896.2.3.139

5. Beaty, R., Benedek, M., Silvia, P., & Schacter, D. (2016). Creative Cognition and Brain Network Dynamics. Trends in Cognitive Sciences, 20. https://doi.org/10.1016/j.tics.2015.10.004

6. Beaty, R. E., Silvia, P. J., Nusbaum, E. C., Jauk, E., & Benedek, M. (2014). The roles of associative and executive processes in creative cognition. Memory & Cognition, 42(7), 1186-1197. https://doi.org/10.3758/s13421-014-0428-8

7. Benedek, M., & Jauk, E. (2018). Spontaneous and Controlled Processes in Creative Cognition. The Oxford Handbook of Spontaneous Thought. https://doi.org/10.1093/oxfordhb/9780190464745.013.22

8. Cassotti, M., Agogué, M., Camarda, A., Houdé, O., & Borst, G. (2016). Inhibitory Control as a Core Process of Creative Problem Solving and Idea Generation from Childhood to Adulthood. New Directions for Child and Adolescent Development, 2016(151), 61-72. https://doi.org/10.1002/cad.20153

9. Chrysikou, E. G. (2019). Creativity in and out of (cognitive) control. Current Opinion in Behavioral Sciences, 27, 94-99. https://doi.org/10.1016/j.cobeha.2018.09.014

10. Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. NeuroImage, 59(2), 1783-1794. https://doi.org/10.1016/j.neuroimage.2011.08.008

11. Kleinmintz, O. M., Ivancovsky, T., & Shamay-Tsoory, S. G. (2019). The two-fold model of creativity : The neural underpinnings of the generation and evaluation of creative ideas. Current Opinion in Behavioral Sciences, 27, 131-138. https://doi.org/10.1016/j.cobeha.2018.11.004

12. Sowden, P., Pringle, A., & Gabora, L. (2015). The shifting sands of creative thinking : Connections to dual-process theory. Thinking & Reasoning, 21, 40-60. https://doi.org/10.1080/13546783.2014.885464

13. Volle, E. (2018). Associative and controlled cognition in divergent thinking : Theoretical, experimental, neuroimaging evidence, and new directions. In The Cambridge handbook of the

neuroscience of creativity (p. 333-360). Cambridge University Press. https://doi.org/10.1017/9781316556238.020

14. Ovando-Tellez, M., Benedek, M., Kenett, Y. N., Hills, T., Bouanane, S., Bernard, M., Belo, J., Bieth, T., & Volle, E. (2022). An investigation of the cognitive and neural correlates of semantic memory search related to creative ability. Communications Biology, 5(1), Article 1. https://doi.org/10.1038/s42003-022-03547-x

15. Beaty, R. E., Zeitlen, D. C., Baker, B. S., & Kenett, Y. N. (2021). Forward flow and creative thought : Assessing associative cognition and its role in divergent thinking. Thinking Skills and Creativity, 41, 100859. https://doi.org/10.1016/j.tsc.2021.100859

16. Wang, X., Zhuang, K., Zhang, J., Cortes, R., Holzman, D., Fan, L., Liu, C., Chen, Q., Sun, J., Li, X., Li, Y., Feng, Q., Chen, H., Feng, T., Lei, X., He, Q., Green, A., & Qiu, J. (2023). Semantic associations and executive control predict Novelty and appropriateness of idea generation respectively and mediated by separate brain connectivity [Preprint]. In Review. https://doi.org/10.21203/rs.3.rs-3691289/v1

17. Kenett, Y. N., Levy, O., Kenett, D. Y., Stanley, H. E., Faust, M., & Havlin, S. (2018). Flexibility of thought in high creative individuals represented by percolation analysis. Proceedings of the National Academy of Sciences, 115(5), 867-872. https://doi.org/10.1073/pnas.1717362115

18. Lin, H., & Vartanian, O. (2018). A Neuroeconomic Framework for Creative Cognition. Perspectives on Psychological Science: A Journal of the Association for Psychological Science, 13(6), 655-677. https://doi.org/10.1177/1745691618794945

19. Lopez-Persem, A., Moreno-Rodriguez, S., Ovando-Tellez, M., Bieth, T., Guiet, S., Brochard, J., & Volle, E. (2023). How subjective idea valuation energizes and guides creative idea generation. American Psychologist. https://doi.org/10.1037/amp0001165

20. Rushworth, M. F. S., & Behrens, T. E. J. (2008). Choice, uncertainty and value in prefrontal and cingulate cortex. Nature Neuroscience, 11(4), Article 4. https://doi.org/10.1038/nn2066

21. Raichle, M. E. (2015). The Brain's Default Mode Network. Annual Review of Neuroscience, 38(1), 433-447. https://doi.org/10.1146/annurev-neuro-071013-014030

22. Zabelina, D. L., & Andrews-Hanna, J. R. (2016). Dynamic network interactions supporting internally-oriented cognition. Current Opinion in Neurobiology, 40, 86-93. https://doi.org/10.1016/j.conb.2016.06.014

23. Liu, S., Erkkinen, M., Healey, M., Xu, Y., Aboud, K., Chow, H., & Braun, A. (2015). Brain activity and connectivity during poetry composition : Toward a multidimensional model of the creative process: Composing Poetry: Process, Product, Expertise. Human Brain Mapping, 36. https://doi.org/10.1002/hbm.22849

24. Lloyd-Cox, J., Chen, Q., & Beaty, R. E. (2022). The time course of creativity : Multivariate classification of default and executive network contributions to creative cognition over time. Cortex, 156, 90-105. https://doi.org/10.1016/j.cortex.2022.08.008

25. Matheson, H. E., Kenett, Y. N., Gerver, C., & Beaty, R. E. (2023). Representing creative thought : A representational similarity analysis of creative idea generation and evaluation. Neuropsychologia, 187, 108587. https://doi.org/10.1016/j.neuropsychologia.2023.108587

26. Mayseless, N., Aharon-Peretz, J., & Shamay-Tsoory, S. (2014). Unleashing creativity : The role of left temporoparietal regions in evaluating and inhibiting the generation of creative ideas. Neuropsychologia, 64, 157-168. https://doi.org/10.1016/j.neuropsychologia.2014.09.022

27. Mayseless, N., Eran, A., & Shamay-Tsoory, S. G. (2015). Generating original ideas : The neural underpinning of originality. NeuroImage, 116, 232-239. https://doi.org/10.1016/j.neuroimage.2015.05.030

28. Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. Cognitive, Affective & Behavioral Neuroscience, 12(2), 241-268. https://doi.org/10.3758/s13415-011-0083-5

29. Huang, F., Tang, S., Sun, P., & Luo, J. (2018). Neural correlates of novelty and appropriateness processing in externally induced constraint relaxation. NeuroImage, 172, 381-389. https://doi.org/10.1016/j.neuroimage.2018.01.070

30. Wu, X., Gu, X., Guo, Q., Hao, X., & Luo, J. (2022). Neural correlates of novelty and appropriateness processing in cognitive reappraisal. Biological Psychology, 170, 108318. https://doi.org/10.1016/j.biopsycho.2022.108318

31. Anticevic, A., Cole, M. W., Murray, J. D., Corlett, P. R., Wang, X.-J., & Krystal, J. H. (2012). The role of default network deactivation in cognition and disease. Trends in Cognitive Sciences, 16(12), 584-592. https://doi.org/10.1016/j.tics.2012.10.008

32. Beaty, R. E., Benedek, M., Barry Kaufman, S., & Silvia, P. J. (2015). Default and Executive Network Coupling Supports Creative Idea Production. Scientific Reports, 5(1), 10964. https://doi.org/10.1038/srep10964

33. Bartra, O., McGuire, J. T., & Kable, J. W. (2013). The valuation system : A coordinate-based meta-analysis of BOLD fMRI experiments examining neural correlates of subjective value. NeuroImage, 76, 412-427. https://doi.org/10.1016/j.neuroimage.2013.02.063

34. Lopez-Persem, A., Bastin, J., Petton, M., Abitbol, R., Lehongre, K., Adam, C., Navarro, V., Rheims, S., Kahane, P., Domenech, P., & Pessiglione, M. (2020). Four core properties of the human brain valuation system demonstrated in intracranial signals. Nature Neuroscience, 23(5), Article 5. https://doi.org/10.1038/s41593-020-0615-9

35. Schultz, W. (2015). Neuronal Reward and Decision Signals : From Theories to Data. Physiological Reviews, 95(3), 853-951. https://doi.org/10.1152/physrev.00023.2014

36. Lebreton, M., Jorge, S., Michel, V., Thirion, B., & Pessiglione, M. (2009). An automatic valuation system in the human brain : Evidence from functional neuroimaging. Neuron, 64(3), 431-439. https://doi.org/10.1016/j.neuron.2009.09.040

37. Levy, D. J., & Glimcher, P. W. (2012). The root of all value : A neural common currency for choice. Current Opinion in Neurobiology, 22(6), 1027-1038. https://doi.org/10.1016/j.conb.2012.06.001

38. Levy, I., Lazzaro, S. C., Rutledge, R. B., & Glimcher, P. W. (2011). Choice from Non-Choice : Predicting Consumer Preferences from Blood Oxygenation Level-Dependent Signals Obtained during Passive Viewing. The Journal of Neuroscience, 31(1), 118-125. https://doi.org/10.1523/JNEUROSCI.3214-10.2011

39. Hare, T. A., Camerer, C. F., & Rangel, A. (2009). Self-control in decision-making involves modulation of the vmPFC valuation system. Science (New York, N.Y.), 324(5927), 646-648. https://doi.org/10.1126/science.1168450

40. Domenech, P., Redouté, J., Koechlin, E., & Dreher, J.-C. (2018). The Neuro-Computational Architecture of Value-Based Selection in the Human Brain. Cerebral Cortex, 28(2), 585-601. https://doi.org/10.1093/cercor/bhw396

41. Beversdorf, D. Q. (2019). Neuropsychopharmacological regulation of performance on creativity-related tasks. Current opinion in behavioral sciences, 27, 55-63. https://doi.org/10.1016/j.cobeha.2018.09.010

42. Huang, F., Fan, J., & Luo, J. (2015). Neural Basis of Novelty and Appropriateness in Processing of Creative Chunk Decomposition. NeuroImage, 113. https://doi.org/10.1016/j.neuroimage.2015.03.030

43. Takeuchi, H., Taki, Y., Sassa, Y., Hashizume, H., Sekiguchi, A., Fukushima, A., & Kawashima, R. (2010). Regional gray matter volume of dopaminergic system associate with creativity : Evidence from voxel-based morphometry. NeuroImage, 51(2), 578-585. https://doi.org/10.1016/j.neuroimage.2010.02.078

44. Aberg, K. C., Doell, K. C., & Schwartz, S. (2016). The “Creative Right Brain” Revisited : Individual Creativity and Associative Priming in the Right Hemisphere Relate to Hemispheric Asymmetries in Reward Brain Function. Cerebral Cortex. https://doi.org/10.1093/cercor/bhw288

45. Boot, N., Baas, M., van Gaal, S., Cools, R., & De Dreu, C. K. W. (2017). Creative cognition and dopaminergic modulation of fronto-striatal networks : Integrative review and research agenda. Neuroscience & Biobehavioral Reviews, 78, 13-23. https://doi.org/10.1016/j.neubiorev.2017.04.007

46. Chermahini, S. A., & Hommel, B. (2010). The (b)link between creativity and dopamine : Spontaneous eye blink rates predict and dissociate divergent and convergent thinking. Cognition, 115(3), 458-465. https://doi.org/10.1016/j.cognition.2010.03.007

47. Zabelina, D. L., Colzato, L., Beeman, M., & Hommel, B. (2016). Dopamine and the Creative Mind : Individual Differences in Creativity Are Predicted by Interactions between Dopamine Genes DAT and COMT. PLOS ONE, 11(1), e0146768. https://doi.org/10.1371/journal.pone.0146768

48. Barron, H., Garvert, M., & Behrens, T. (2015). Reassessing VMPFC : Full of confidence? Nature neuroscience, 18, 1064-1066. https://doi.org/10.1038/nn.4076

49. Lebreton, M., Abitbol, R., Daunizeau, J., & Pessiglione, M. (2015). Automatic integration of confidence in the brain valuation signal. Nature Neuroscience, 18(8), 1159-1167. https://doi.org/10.1038/nn.4064

50. Andreoni, J., & Miller, J. (2002). Giving According to GARP : An Experimental Test of the Consistency of Preferences for Altruism. Econometrica, 70(2), 737.

51. Lopez-Persem, A., Rigoux, L., Bourgeois-Gironde, S., Daunizeau, J., & Pessiglione, M. (2017). Choose, rate or squeeze : Comparison of economic value functions elicited by different behavioral tasks. PLOS Computational Biology, 13(11), e1005848. https://doi.org/10.1371/journal.pcbi.1005848

52. De Martino, B., & Cortese, A. (2023). Goals, usefulness and abstraction in value-based choice. Trends in Cognitive Sciences, 27(1), 65-80. https://doi.org/10.1016/j.tics.2022.11.001

53. Holton, E., Grohn, J., Ward, H., Manohar, S., O'Reilly, J., & Kolling, N. (2023). VmPFC supports persistence during goal pursuit through selective attention [Preprint]. Neuroscience. https://doi.org/10.1101/2023.08.07.552276

54. Juechems, K., & Summerfield, C. (2019). Where Does Value Come From? Trends in Cognitive Sciences, 23(10), 836-850. https://doi.org/10.1016/j.tics.2019.07.012

55. Trudel, N., Scholl, J., Klein-Flügge, M. C., Fouragnan, E., Tankelevitch, L., Wittmann, M. K., & Rushworth, M. F. S. (2021). Polarity of uncertainty representation during exploration and exploitation in ventromedial prefrontal cortex. Nature Human Behaviour, 5(1), 83-98. https://doi.org/10.1038/s41562-020-0929-3

56. Clairis, N., & Pessiglione, M. (2022). Value, Confidence, Deliberation : A Functional Partition of the Medial Prefrontal Cortex Demonstrated across Rating and Choice Tasks. The Journal of Neuroscience, 42(28), 5580-5592. https://doi.org/10.1523/JNEUROSCI.1795-21.2022

57. Rouault, M., Lebreton, M., & Pessiglione, M. (2022). A shared brain system forming confidence judgment across cognitive domains (p. 2021.09.17.460809). bioRxiv. https://doi.org/10.1101/2021.09.17.460809

58. Wittmann, B. C., Daw, N. D., Seymour, B., & Dolan, R. J. (2008). Striatal Activity Underlies Novelty-Based Choice in Humans. Neuron, 58(6), 967-973. https://doi.org/10.1016/j.neuron.2008.04.027

59. Bunzeck, N., & Düzel, E. (2006). Absolute Coding of Stimulus Novelty in the Human Substantia Nigra/VTA. Neuron, 51(3), 369-379. https://doi.org/10.1016/j.neuron.2006.06.021

60. Wittmann, B. C., Bunzeck, N., Dolan, R. J., & Düzel, E. (2007). Anticipation of novelty recruits reward system and hippocampus while promoting recollection. NeuroImage, 38(1), 194-202. https://doi.org/10.1016/j.neuroimage.2007.06.038

61. Düzel, E., Bunzeck, N., Guitart-Masip, M., & Düzel, S. (2010). NOvelty-related Motivation of Anticipation and exploration by Dopamine (NOMAD) : Implications for healthy aging. Neuroscience & Biobehavioral Reviews, 34(5), 660-669. https://doi.org/10.1016/j.neubiorev.2009.08.006

62. Gao, Z., Liu, X., Zhang, D., Liu, M., & Hao, N. (2021). Subcortical structures and visual divergent thinking : A resting-state functional MRI analysis. Brain Structure and Function, 226, 1-11. https://doi.org/10.1007/s00429-021-02355-z

63. Yeo, B. T. T., Krienen, F. M., Sepulcre, J., Sabuncu, M. R., Lashkari, D., Hollinshead, M., Roffman, J. L., Smoller, J. W., Zöllei, L., Polimeni, J. R., Fischl, B., Liu, H., & Buckner, R. L. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. Journal of Neurophysiology, 106(3), 1125-1165. https://doi.org/10.1152/jn.00338.2011

64. Oh, Y., Chesebrough, C., Erickson, B., Zhang, F., & Kounios, J. (2020). An insight-related neural reward signal. NeuroImage, 214, 116757. https://doi.org/10.1016/j.neuroimage.2020.116757

65. Beaty, R. E., Cortes, R. A., Zeitlen, D. C., Weinberger, A. B., & Green, A. E. (2021). Functional Realignment of Frontoparietal Subnetworks during Divergent Creative Thinking. Cerebral Cortex (New York, N.Y.: 1991), 31(10), 4464-4476. https://doi.org/10.1093/cercor/bhab100

66. Hare, T. A., Malmaud, J., & Rangel, A. (2011). Focusing Attention on the Health Aspects of Foods Changes Value Signals in vmPFC and Improves Dietary Choice. Journal of Neuroscience, 31(30), 11077-11087. https://doi.org/10.1523/JNEUROSCI.6383-10.2011

67. Kahnt, T., Heinzle, J., Park, S. Q., & Haynes, J.-D. (2011). Decoding different roles for vmPFC and dlPFC in multi-attribute decision making. NeuroImage, 56(2), 709-715. https://doi.org/10.1016/j.neuroimage.2010.05.058

68. Magrabi, A., Ludwig, V. U., Stoppel, C. M., Paschke, L. M., Wisniewski, D., Heekeren, H. R., & Walter, H. (2022). Dynamic computation of value signals via a common neural network in multi-attribute decision-making. Social Cognitive and Affective Neuroscience, 17(7), 683-693. https://doi.org/10.1093/scan/nsab125

69. Hunt, L. T., Dolan, R. J., & Behrens, T. E. J. (2014). Hierarchical competitions subserving multi-attribute choice. Nature Neuroscience, 17(11), 1613-1622. https://doi.org/10.1038/nn.3836

70. Busemeyer, J. R., Gluth, S., Rieskamp, J., & Turner, B. M. (2019). Cognitive and Neural Bases of Multi-Attribute, Multi-Alternative, Value-based Decisions. Trends in Cognitive Sciences, 23(3), 251-263. https://doi.org/10.1016/j.tics.2018.12.003

71. Benedek, M., Nordtvedt, N., Jauk, E., Koschmieder, C., Pretsch, J., Krammer, G., & Neubauer, A. (2016). Assessment of creativity evaluation skills : A psychometric investigation in prospective teachers. Thinking Skills and Creativity, 21. https://doi.org/10.1016/j.tsc.2016.05.007

72. Kleinmintz, O. M., Goldstein, P., Mayseless, N., Abecasis, D., & Shamay-Tsoory, S. G. (2014). Expertise in Musical Improvisation and Creativity : The Mediation of Idea Evaluation. PLoS ONE, 9(7), e101568. https://doi.org/10.1371/journal.pone.0101568

73. Diedrich, J., Benedek, M., Jauk, E., & Neubauer, A. (2015). Are creative ideas novel and useful. https://doi.org/10.1037/A0038688

74. Mueller, J. S., Melwani, S., & Goncalo, J. A. (2012). The Bias Against Creativity : Why People Desire but Reject Creative Ideas. Psychological Science, 23(1), 13-17. https://doi.org/10.1177/0956797611421018

75. Zhu, Y., Ritter, S. M., Müller, B. C. N., & Dijksterhuis, A. (2017). Creativity : Intuitive processing outperforms deliberative processing in creative idea selection. Journal of Experimental Social Psychology, 73, 180-188. https://doi.org/10.1016/j.jesp.2017.06.009

76. Bendetowicz, D., Urbanski, M., Garcin, B., Foulon, C., Levy, R., Bréchemier, M.-L., Rosso, C., Thiebaut De Schotten, M., & Volle, E. (2018). Two critical brain networks for generation and combination of remote associations. Brain, 141(1), 217-233. https://doi.org/10.1093/brain/awx294

77. Diedrich, J., Jauk, E., Silvia, P. J., Gredlein, J. M., Neubauer, A. C., & Benedek, M. (2018). Assessment of real-life creativity : The Inventory of Creative Activities and Achievements (ICAA). Psychology of Aesthetics, Creativity, and the Arts, 12(3), 304-316. https://doi.org/10.1037/aca0000137

78. Barbot, B. (2018). The Dynamics of Creative Ideation : Introducing a New Assessment Paradigm. Frontiers in Psychology, 9. https://www.frontiersin.org/articles/10.3389/fpsyg.2018.02529

79. Ceh, S. M., Edelmann, C., Hofer, G., & Benedek, M. (2022). Assessing Raters : What Factors Predict Discernment in Novice Creativity Raters? The Journal of Creative Behavior, 56(1), 41-54. https://doi.org/10.1002/jocb.515

80. 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. https://doi.org/10.1016/j.cortex.2016.10.021

81. Mednick, S. (1962). The associative basis of the creative process. Psychological Review, 69, 220-232. https://doi.org/10.1037/h0048850

82. Benedek, M., Könen, T., & Neubauer, A. (2012). Associative Abilities Underlying Creativity. Psychology of Aesthetics, Creativity, and the Arts, 6, 273-281. https://doi.org/10.1037/a0027059

83. Debrenne, M. (2011). Le dictionnaire des associations verbales du français et ses applications. Variétés, variations and formes du français. Palaiseau: Éditions de l'Ecole polytechnique, 355, 366.

84. Daunizeau, J., Friston, K. J., & Kiebel, S. J. (2009). Variational Bayesian identification and prediction of stochastic nonlinear dynamic causal models. Physica D: Nonlinear Phenomena, 238(21), 2089-2118. https://doi.org/10.1016/j.physd.2009.08.002

85. DuPre, E., Salo, T., Ahmed, Z., Bandettini, P., Bottenhorn, K., Caballero-Gaudes, C., Dowdle, L., Gonzalez-Castillo, J., Heunis, S., Kundu, P., Laird, A., Markello, R., Markiewicz, C., Moia, S., Staden, I., Teves, J., Uruñuela, E., Vaziri-Pashkam, M., Whitaker, K., & Handwerker, D. (2021). TE-dependent analysis of multi-echo fMRI with tedana. Journal of Open Source Software, 6(66), 3669. https://doi.org/10.21105/joss.03669

86. Gaser, C., Dahnke, R., Thompson, P. M., Kurth, F., Luders, E., & Alzheimer's Disease Neuroimaging Initiative. (2022). CAT – A Computational Anatomy Toolbox for the Analysis of Structural MRI Data. https://doi.org/10.1101/2022.06.11.495736

87. Frässle, S., Aponte, E. A., Bollmann, S., Brodersen, K. H., Do, C. T., Harrison, O. K., Harrison, S. J., Heinzle, J., Iglesias, S., Kasper, L., Lomakina, E. I., Mathys, C., Müller-Schrader, M., Pereira, I., Petzschner, F. H., Raman, S., Schöbi, D., Toussaint, B., Weber, L. A., … Stephan, K. E. (2021).

TAPAS : An Open-Source Software Package for Translational Neuromodeling and Computational Psychiatry. Frontiers in Psychiatry, 12.
https://www.frontiersin.org/journals/psychiatry/articles/10.3389/fpsyt.2021.680811

88. Glover, G. H., Li, T. Q., & Ress, D. (2000). Image-based method for retrospective correction of physiological motion effects in fMRI : RETROICOR. Magnetic Resonance in Medicine, 44(1), 162-167. https://doi.org/10.1002/1522-2594(200007)44:1<162::aid-mrm23>3.0.co;2-e

89. Yarkoni, T., Poldrack, R. A., Nichols, T. E., Van Essen, D. C., & Wager, T. D. (2011). Large-scale automated synthesis of human functional neuroimaging data. Nature Methods, 8(8), 665-670. https://doi.org/10.1038/nmeth.1635

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Conceptualization: EV, ALP, SMR
Data collection: SMR
Analyses: SMR, ALP
fMRI preprocessing: BB
Writing - original draft: SMR, ALP, EV
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Data and materials availability:
The dataset is composed of demographic data, behavioral data and functional and anatomical MRI data for the forty participants. Data and code can be found on the OSF platform (insert link here*).
*Data and code will be made available to all upon publication.

Figures and Tables

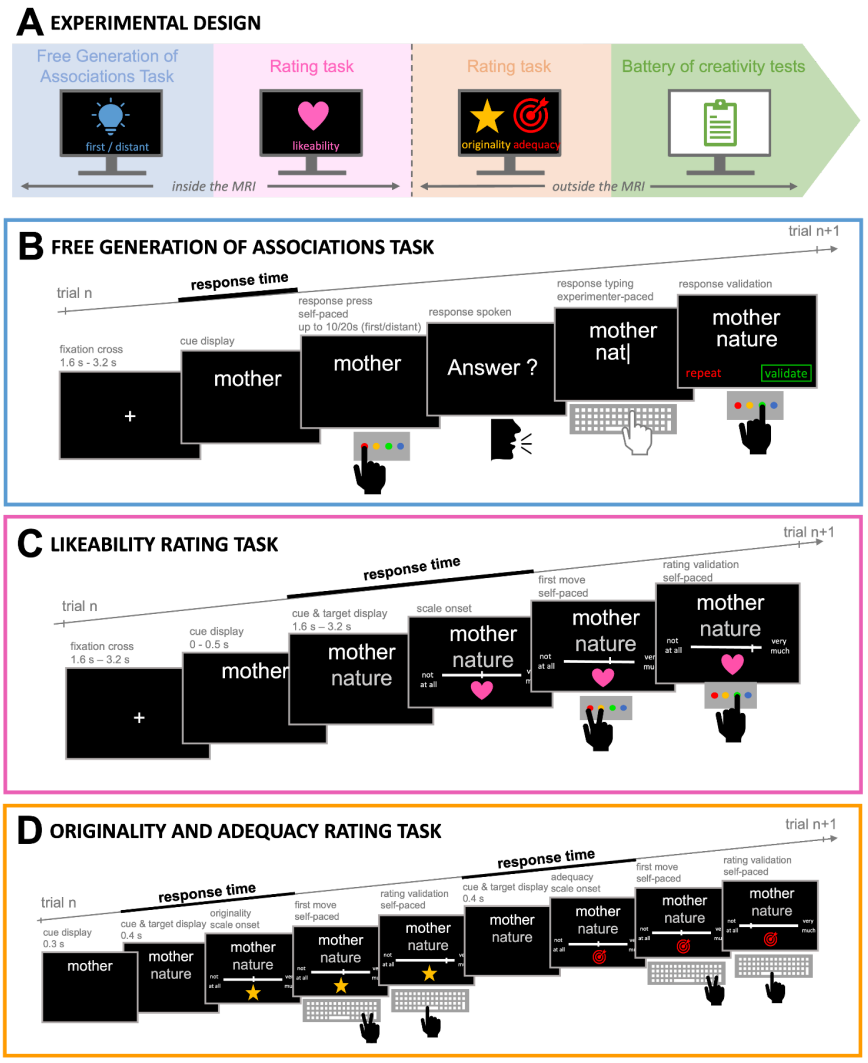

Figure 1: Experimental design (A) Overview of the different tasks in chronological order **(B)** Free Generation of Association Task (FGAT). In two conditions ("first" and "distant"), participants had to provide, respectively: the first word that came to their mind when they saw the cue word or an unusual, original, but associated word. Participants in the MRI provided their responses orally to the experimenter, who typed them. They had the opportunity to repeat their response in case the experimenter had misheard. **(C)** Likeability rating task. Participants rated each association on a likeability scale from "not at all" to "very much" and validated the rating using MRI response buttons. **(D)** Originality and adequacy rating task. Participants rated each association on a scale going from "not at all" to "very much" using the keyboard arrows and validated the rating using the spacebar. In the MRI, all trials of all tasks began with a fixation cross, followed by the trial screen. Participants also completed a choice task in the MRI scanner, for which data were not analyzed for the current study.

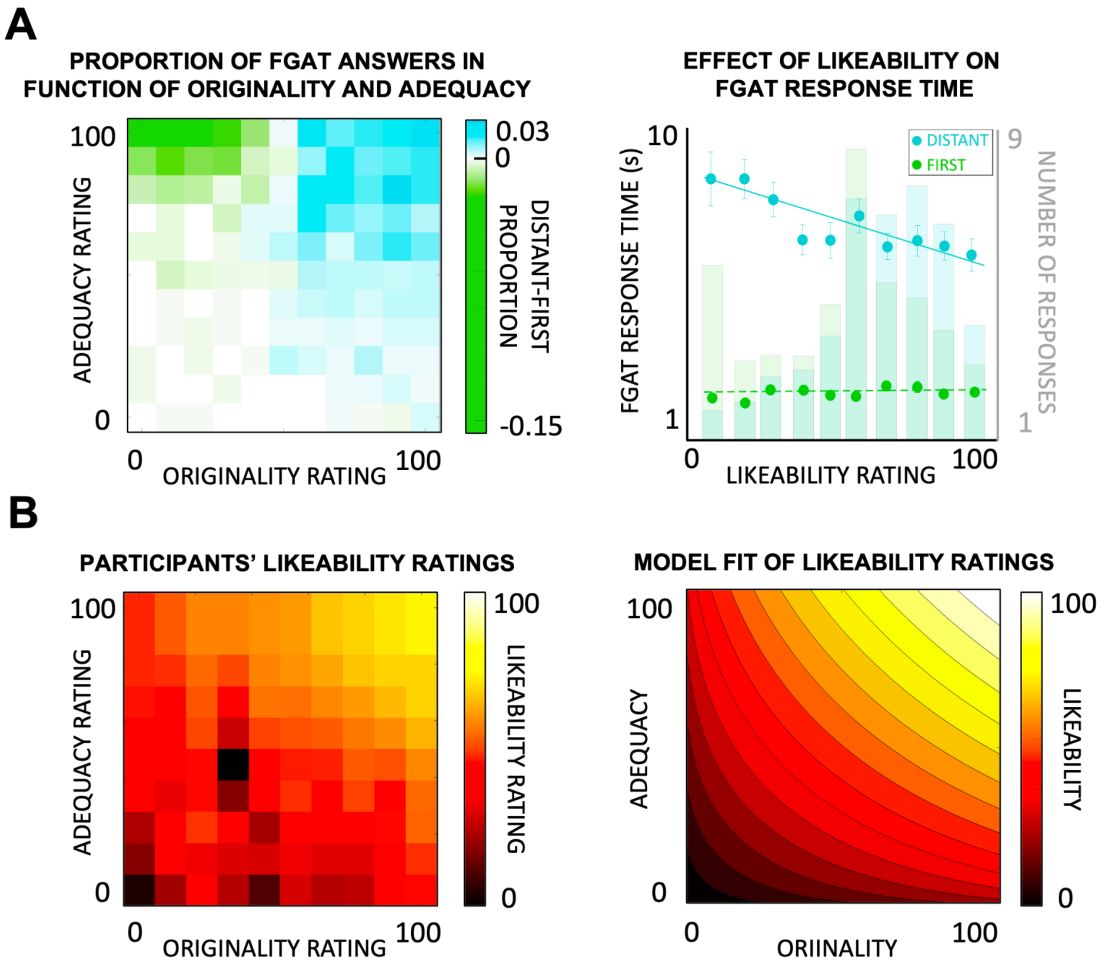

Figure 2: Behavioral results of creative idea production and evaluation. (A) Creative idea production. **Left:** Heatmap of the difference in proportion between "distant" and "first" associations per bin of adequacy and originality ratings. Bins with positive values count more "distant" answers than "first" answers and vice versa. **Right:** Correlation between response time and likeability ratings of the FGAT responses for the "first" and "distant" conditions. Background bars indicate the mean number of answers per bin of likeability ratings. Circles are bins of averaged participant data. Error bars are intersubject standard errors of the mean (SEM). Lines correspond to the linear regression fit at the group level in the "distant" condition (significant fit, $p<0.05$) and the "first" condition (non-significant fit, $p>0.05$). **(B)** Creative idea evaluation. **Left:** Heatmap of participants' average likeability ratings per bin of adequacy and originality ratings. **Right**: CES model fit of likeability ratings in function of adequacy and originality ratings. The verticality of isolines is captured by the α parameter (preference for originality), while the convexity of isolines is captured by the δ parameter (preference for a trade-off of both dimensions rather than extremes).

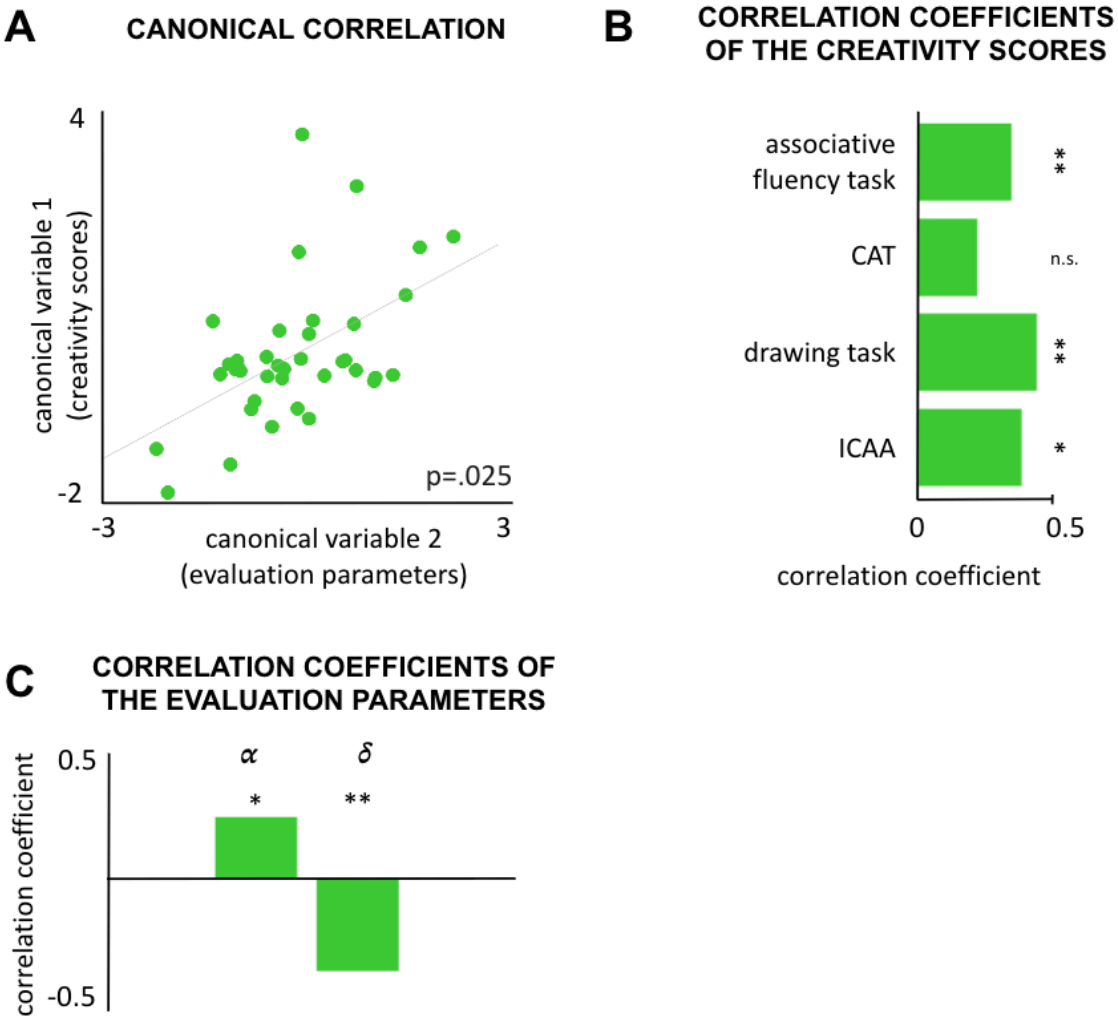

Figure 3: Canonical correlation between evaluation parameters and creative abilities. (A) Canonical correlation between creativity scores in battery tests and evaluation parameters (α and δ) from the behavioral analyses. Each circle represents one participant. The line represents a significant correlation ($p<0.05$). **(B)** Correlation coefficients of the creativity scores from the battery of tests. **(C)** Correlation coefficients of the evaluation parameters. * and ** indicate statistical significance (respectively $p<0.05$ and $p<0.01$). n.s. stands for not significant ($p>0.05$).

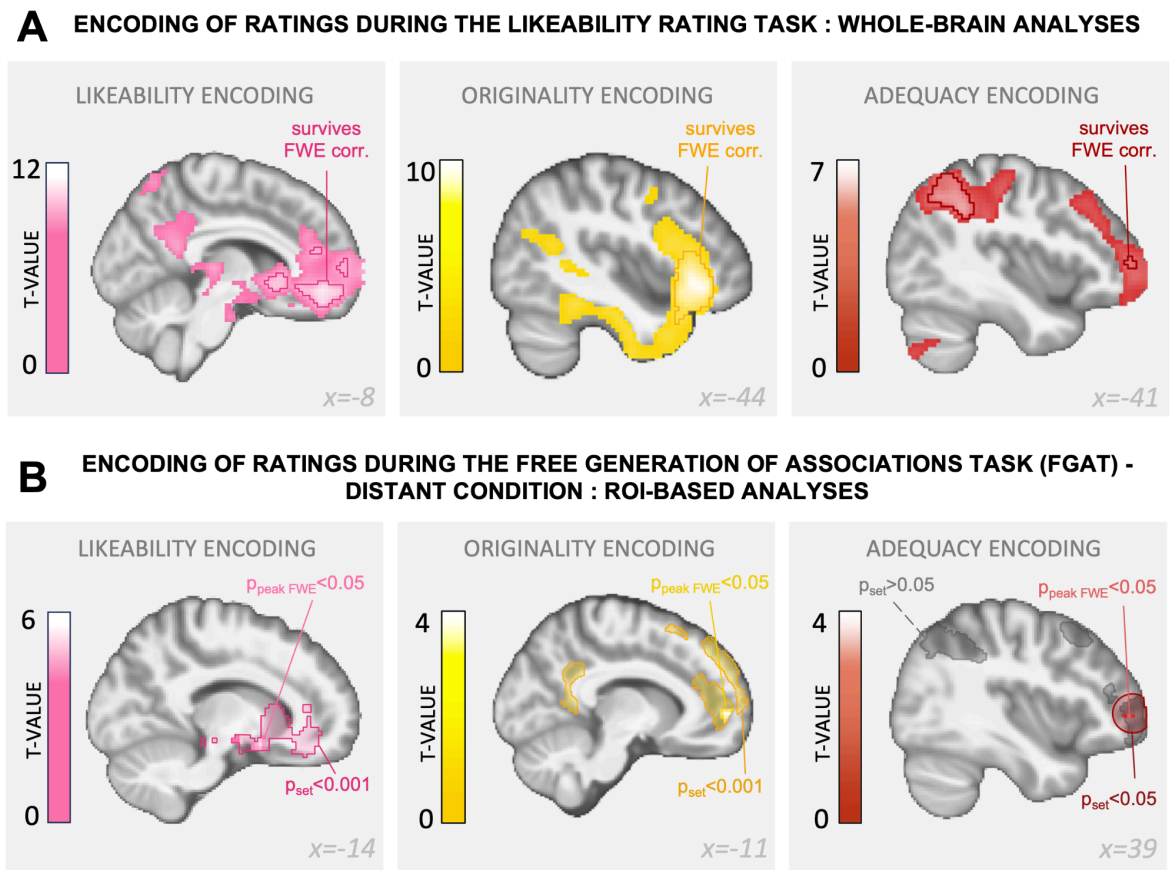

Figure 4: Neuroimaging results of likeability, originality and adequacy encoding during the likeability rating task and the FGAT-distant. (A) Neural encoding of likeability ratings (pink), originality ratings (yellow) and adequacy ratings (red) during the likeability rating task. The color code indicates the T-value of one-sample t-tests, $p<0.001$ uncorrected. Circled regions survived cluster-level FWE correction ($p<0.05$). See Table 1 for all significant clusters. **(B)** Neural encoding of likeability ratings (pink), originality ratings (yellow) and adequacy ratings (red) during the FGAT-distant. Circled regions are the overlap of the regions in A and their most similar atlas network (as depicted in Figure 5). They were used as inclusive masks for small volume correction, to identify significant peaks with FWE correction ($p<0.05$). Colored circled regions are significant at the set level ($p<0.001$); grey circled regions are not significant at the set level ($p>0.05$). The color code of the peaks within the masks indicates the T-value of one-sample t-tests, displayed at $p<0.001$ but surviving FWE correction ($p<0.05$) within the mask. See Table 2 for more information.

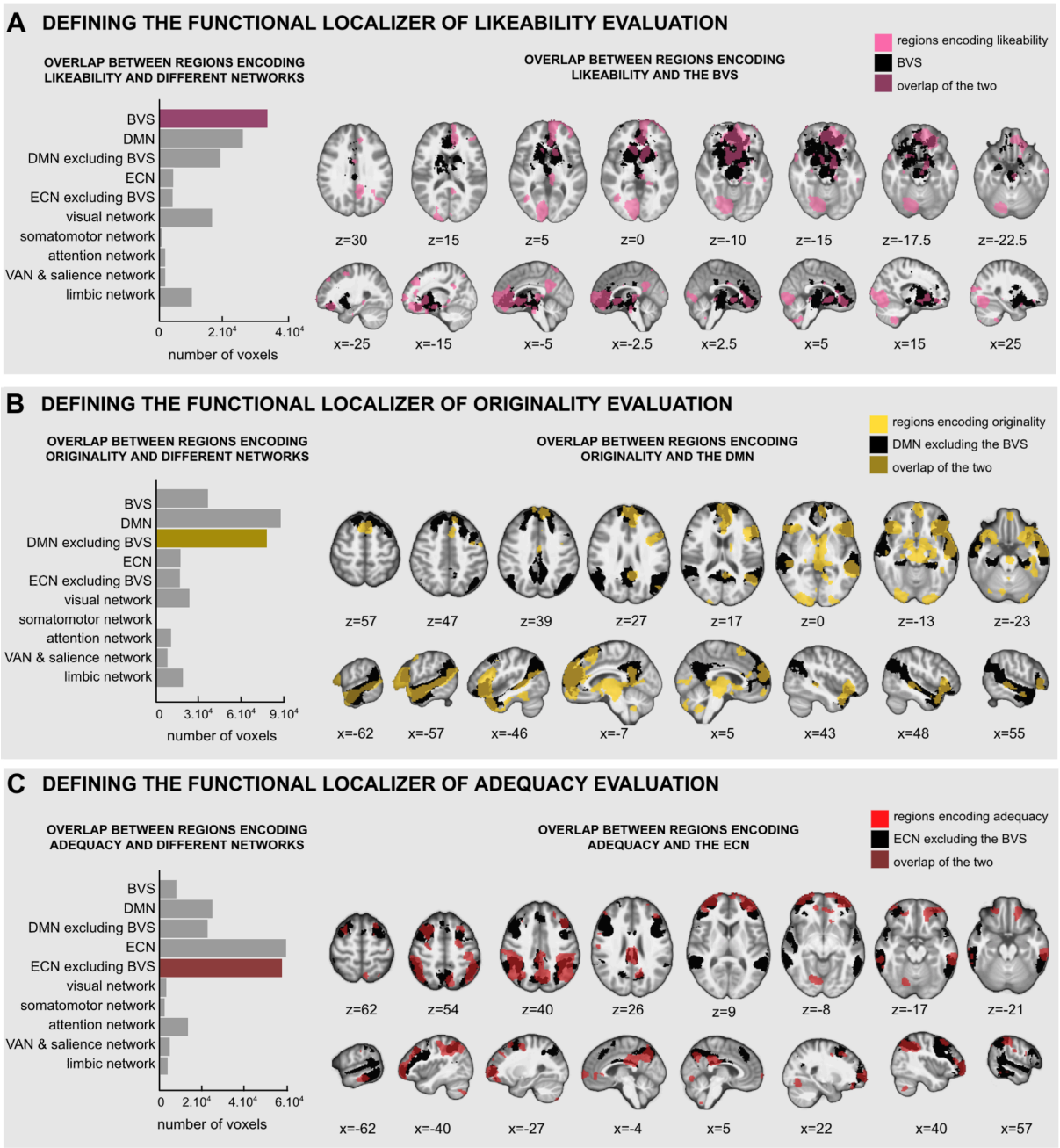

Figure 5: Defining the function localizers of likeability, originality and adequacy evaluation using brain networks overlaps. Left: Number of common voxels between the statistical maps of the parametric modulation of the likeability rating task by **(A)** likeability, **(B)** originality and **(C)** adequacy ratings, with networks of interest as defined by Yeo et al. **(52)** and Neurosynth. See Table S1 for all inter-network overlaps. **Right:** Visual of the overlap between the regions encoding each dimension (colour) and the principal network (black) as defined by Yeo et al. **(52)** and Neurosynth.

PARAMETRIC MODULATION DURING THE LIKEABILITY RATING TASK

parametric modulator: **likeability rating**									
cluster label	cluster size	peak side	x	y	z	Z-score	T-value	cluster p-value	network of interest?
occipital cortex	804	R	6	-82	-2	>8	12.81	<10-16	none
ventromedial prefrontal cortex	**324**	**L**	**-8**	**48**	**-10**	**6.15**	**8.20**	**5.10-15**	**DMN**
ventral striatum	**91**	**L**	**-14**	**22**	**0**	**5.84**	**7.55**	**1.10-7**	**BVS**
ventral striatum	**57**	**R**	**12**	**22**	**-2**	**5.54**	**6.98**	**4.10-6**	**BVS**
cerebellum	30	R	12	-52	-50	5.36	6.65	1.10-4	none
anterior cingulate cortex	18	L	-11	42	16	5.33	6.60	6.10-4	DMN
medial frontal pole	13	L	-8	60	6	4.94	5.92	0.002	DMN
midbrain	1	L	-6	-18	-24	4.89	5.85	0.027	BVS
parametric modulator: **originality rating**									
cluster label	cluster size	peak side	x	y	z	Z-score	T-value	cluster p-value	network of interest?
inferior frontal gyrus	**1163**	**L**	**-44**	**28**	**-4**	**7.44**	**11.46**	**<10-16**	**none**
middle temporal gyrus	**543**	**L**	**-56**	**-15**	**-12**	**6.64**	**9.30**	**<10-16**	**DMN**
dorsomedial prefrontal cortex	**320**	**L**	**-6**	**48**	**16**	**6.55**	**9.10**	**3.10-15**	**DMN**
lateral orbitofrontal cortex	**105**	**R**	**39**	**30**	**-10**	**5.85**	**7.57**	**3.10-8**	**BVS**
pre-supplementary motor area	**72**	**L**	**-4**	**20**	**58**	**5.80**	**7.48**	**6.10-7**	**DMN**
ventral tegmental area	27	L	-4	-22	-20	5.78	7.43	1.10-4	BVS
lateral orbitofrontal cortex	35	R	26	18	-22	5.63	7.16	5.10-5	none
medial frontal pole	31	L	-4	62	-14	5.54	6.99	8.10-5	BVS
occipital cortex	49	L	-18	-95	-7	5.54	6.99	8.10-6	none
cerebellum	31	R	2	-55	-42	5.49	6.89	8.10-5	none
brainstem	150	L	-4	-30	-2	5.47	6.84	5.10-10	BVS
occipital cortex	87	R	24	-90	-4	5.38	6.68	1.10-7	none
cerebellum	39	R	19	-78	-40	5.37	6.66	3.10-5	none
fusiform gyrus	10	L	-34	-8	-42	5.15	6.29	0.002	none
amygdala	7	L	-16	-2	-17	4.95	5.95	0.005	BVS
temporal pole	3	R	42	15	-27	4.91	5.88	0.013	none
fusiform gyrus	2	L	-38	-10	-37	4.85	5.78	0.018	none
posterior cingulate cortex	3	L	-8	-50	30	4.82	5.74	0.013	DMN
globus pallidus	3	R	14	0	-14	4.82	5.73	0.013	BVS
inferior frontal gyrus	1	L	-48	18	20	4.77	5.65	0.026	ECN
cerebellum	1	R	22	-40	-47	4.75	5.63	0.026	none
parametric modulator: **adequacy rating**									
cluster label	cluster size	peak side	x	y	z	Z-score	T-value	cluster p-value	network of interest?
precuneus	**192**	**L**	**-6**	**-70**	**38**	**5.96**	**7.80**	**3.10-11**	**ECN**
intraparietal lobule	**398**	**L**	**-41**	**-48**	**38**	**5.95**	**7.77**	**1.10-16**	**ECN**
posterior cingulate cortex	**129**	**L**	**-6**	**-25**	**30**	**5.86**	**7.59**	**5.10-9**	**ECN & BVS**
lateral frontal pole	**110**	**L**	**-36**	**52**	**3**	**5.74**	**7.36**	**4.10-6**	**ECN**
intraparietal lobule	**122**	**R**	**44**	**-38**	**43**	**5.57**	**7,04**	**9.10-9**	**ECN**
inferior temporal sulcus	**34**	**L**	**-61**	**-30**	**-17**	**5.28**	**6.50**	**7.10-5**	**DMN**
cerebellum	15	R	44	-65	-50	5.23	6.41	0.001	none
lateral frontal pole	**55**	**R**	**34**	**62**	**6**	**5.12**	**6.24**	**5.10-6**	**ECN**
lingual gyrus	10	R	6	-78	-7	5.08	6.17	0.003	none
lingual gyrus	10	R	16	-72	-12	5.04	6.10	0.003	none
medial frontal pole	9	L	-8	75	3	4.94	5.93	0.003	none
supramarginal gyrus	2	L	-51	-35	43	4.78	5.66	0.019	ECN
lateral frontal pole	2	R	42	62	-12	4.76	5.64	0.019	none

Table 1: All significant clusters in the SPMs of the parametric modulation analyses during the rating task. The clusters listed here survived whole-brain cluster-level FWE correction ($p<0.05$). Coordinates x, y and z refer to the Montreal Neurological Institute space. The last column indicates whether the peak activation location falls within a network of interest. DMN and ECN are defined by Yeo et al.'s atlas (52), and BVS is defined by the term-based meta-analyses of the Neurosynth platform https://neurosynth.org/analyses/terms/reward/). Only the results in bold are reported in the text.

PARAMETRIC MODULATION DURING THE FREE GENERATION OF ASSOCIATIONS TASK – DISTANT CONDITION

parametric modulator: **likeability rating**									
mask								set p-value	
overlap of the likeablity rating localizer with the BVS (Neurosynth metanalysis)								**0.007**	
cluster label	cluster size	peak side	x	y	z	Z-score	T-value	peak p-value	cluster p-value
ventral striatum	29	L	-14	8	-14	04.09	4.64	0.015	**0.0501**
parametric modulator: **originality rating**									
mask								set p-value	
overlap of the originality rating localizer with the DMN (Yeo et al., 2011) excluding the BVS								**3.10-4**	
cluster label	cluster size	peak side	x	y	z	Z-score	T-value	peak p-value	cluster p-value
medial frontal pole	20	L	-11	55	0	4.1	4.68	0.044	**0.215**
parametric modulator: **adequacy rating**									
mask								set p-value	
overlap of the adequacy rating localizer and the ECN (Yeo et al., 2011) excluding the BVS								**0.292**	
cluster label	cluster size	peak side	x	y	z	Z-score	T-value	peak p-value	cluster p-value
dorsolateral prefrontal cortex	8	R	44	42	13	3.77	4.20	0.127	0.355
lateral frontal pole	8	R	42	55	0	3.30	3.59	0.445	0.355
mask									
10-voxel radius sphere centered on the 1st peak activation in the adequacy rating localizer (x=-6 y=-70 z=38)								no suprathreshold clusters	
mask									
10-voxel radius sphere centered on the 2nd peak activation in the adequacy rating localizer (x=-41 y=-48 z=38)								no suprathreshold clusters	
mask									
10-voxel radius sphere centered on the 3rd peak activation in the adequacy rating localizer (x=-36 y=52 z=3)								no suprathreshold clusters	
mask									
10-voxel radius sphere centered on the 4th peak activation in the adequacy rating localizer (x=44 y=-38 z=43)								no suprathreshold clusters	
mask								set p-value	
10-voxel radius sphere centered on the 5th peak activation in the adequacy rating localizer (x=34 y=62 z=6)								**0.049**	
cluster label	cluster size	peak side	x	y	z	Z-score	T-value	peak p-value	cluster p-value
lateral frontal pole	2	R	39	58	0	3.13	3.37	**0.045**	0.035

Table 2: All clusters in the SPMs of the parametric modulation analyses during the FGAT-distant. Only the results in bold are reported in the text. p-values are FWE corrected. Coordinates x, y and z refer to the Montreal Neurological Institute space. Only the results in bold are reported in the text.

Supplementary

1. *Supplementary results*

Below are supplementary control analyses mentioned in the main text.

Individuals provide preferred responses faster: control analyses.
Importantly, we took into consideration the quadratic relationship that exists between likeability ratings and confidence, as it has been shown that people are more confident in high and low likeability ratings and more uncertain for intermediate ratings (48,49). We sought to confirm that the effect of likeability on response times was a marker of valuation and not confidence. To do so, we introduced the squared normalized likeability ratings as an additional regressor alongside the likeability ratings in the general linear model (GLM) of response times. We found that likeability had a stronger impact on response times compared to the squared likeability ratings ($\beta_{likeability}$=-0.17±0.03, t(37)=-6.66, p=8.10^{-8}; $\beta_{likeability^2}$=0.01±0.02, t(37)=0.38, p=0.71; paired two-tailed t-test: t(37)=-6.87, p=4.10^{-8}), confirming that the effect of likeability on response times was a marker of valuation and not confidence.

Locating the neural encoding of likeability during idea production: control analyses of response times neural correlates
As response times negatively correlated with likeability ratings in FGAT-distant, we conducted a control analysis using a whole-brain parametric modulation approach, with response time as a regressor. During the rating task, the response times were encoded in several regions (Figure S2), namely in the insula ([-44, 0, -4], t(37)=10.81, pFWE<10^{-16}) and parietal operculum ([52, -35, 26], t(37)=10.52, pFWE<10^{-16}). During FGAT-distant, response times were mainly encoded in the lateral frontal pole ([32, 50, 23], t(37)=7.62, pFWE=2.10^{-10}) and the supramarginal gyrus ([62, -48, 28], t(37)=7.28, pFWE=1.10^{-11}). We found no significant correlation between response times and the BOLD signal in regions of the BVS during the likeability rating task or FGAT-distant (see Table S2 for all significant clusters).

2. *Supplementary methods*

Below are supplementary tasks instructions details mentioned in the main text.

FGAT instructions
In the FGAT, we divided instructions into successive slides, illustrated with screenshots of what the task would look like, and participants read them at their own pace. The instructions were as follows (translated from French):

FGAT-first: “In each trial, you will see a word appear on the screen. You will have to state the first word that comes to your mind without thinking and as fast as possible. As soon as you have a word in mind, you will need to press your index finger to give your response to the experimenter. The word "Response?" will then appear on the screen: you can say the word out loud to the experimenter. The experimenter will write down the word heard. You must verify that it is indeed the word you said. If yes, press with your ring finger to confirm your answer. If not, press with your index finger to repeat your response. Please note that this is only to confirm that the word has been heard correctly. You do not have the right to change your mind. Once your answer is confirmed, a new word will appear on the screen; proceed in the same way. Be aware! You will have 10 seconds to think of your response. If you take too long to find an answer, we will move on to the next trial. Before pressing with your index

finger, wait until you have an answer in mind: you must say it directly to the experimenter without taking additional time to think. Conjugated verbs, proper nouns, and groups of words are not accepted."

FGAT-distant: "Similar to the previous task, with each new trial, you will see a word appear on the screen. This time, you must respond with a word that is not typically associated with the displayed word but is still somehow related. Think creatively: the association between the displayed word and your response should be original, unusual, surprising, while still being understandable to someone else. As soon as you have a word in mind, you will need to press your index finger to give your response to the experimenter. The word "Response?" will then appear on the screen: you can say the word out loud to the experimenter. The experimenter will write down the word heard. You must verify that it is indeed the word you said. If yes, press with your ring finger to confirm your answer. If not, press with your index finger to repeat your response. Please note that this is only to confirm that the word has been heard correctly. You do not have the right to change your mind. Once your answer is confirmed, a new word will appear on the screen; proceed in the same way. Be aware! You will have 20 seconds to think of your response. If you take too long to find an answer, we will move on to the next trial. Before pressing with your index finger, wait until you have an answer in mind: you must say it directly to the experimenter without taking additional time to think. Conjugated verbs, proper nouns, and groups of words are not accepted."

Rating task instructions

For the likeability rating task, we divided instructions into successive slides, illustrated with screenshots of what the task would look like, and participants read them at their own pace. The instructions were as follows (translated from French):

"As a reminder, at the beginning of this experiment, you performed two tasks. In response to a word (for example, "jewelry"), you were required to give two types of responses: the first response that comes to your mind (for example, "jewelry-necklace") and an unusual but understandable response (for example, "jewelry-money"). In this task, with each new trial, you will see a pair of words on the screen. The first word is part of the words you have seen in the previous tasks. The second word is a word possibly associated with the first word, which can be a word you proposed in the previous tasks or another suggestion. The task is to indicate how much you like the association between these two words in the context of the previous task (where you had to provide an unusual response). For example, how much would you have liked to respond with the word "necklace" to the word "jewelry" in the previous task? Below the association, an evaluation scale will appear, with a heart. Using this scale, you will indicate how much you like this association. Move the cursor using your index and middle fingers. Confirm your response by pressing with your ring finger. Be aware! You must move the cursor, even if you are perfectly neutral (in this case, move and return the cursor to the middle). Use the entire scale: do not always respond the same way! Reminder: Indicate how much you would have liked to propose the second word of the association in response to the previous task (unusual response). If it's a response you have given before, indicate how satisfied you are with that response."

For the originality and adequacy rating task, we divided instructions into successive slides, illustrated with screenshots of what the task would look like, and participants read them at their own pace. The instructions were as follows (translated from French):
"As a reminder, at the beginning of this experiment, you performed two tasks. In response to a word (for example, "jewelry"), you were required to give two types of responses: the first response that comes to your mind (for example, "jewelry-necklace") and an unusual but understandable response

(for example, "jewelry-money"). Similar to the previous task, with each new trial, you will see a pair of words on the screen. You will evaluate this word association based on two specific criteria. Firstly, does this association seem appropriate to you, meaning understandable, relevant, fitting? To respond, a relevance evaluation scale will appear. Move the cursor using the "left arrow" and "right arrow" keys. Confirm your response by pressing "space." If the association seems entirely relevant to you, move the cursor to the right. If you do not see a connection between the words, move the cursor to the left. Any evaluation between these two extremes is possible. Once your response is confirmed, you will evaluate a second criterion, that of the originality of this word association: how unusual and surprising you find this association. For this, a second evaluation scale will appear. This scale will allow you to indicate how original you think the association is. Move the cursor using the "left arrow" and "right arrow" keys. Confirm your response by pressing "space." Be aware! You must move the cursor, even if you are perfectly neutral (in this case, move and return the cursor to the middle). Try to use the entire scale: do not always respond the same way."

Choice task instructions

For the Choice task, we divided instructions into successive slides, illustrated with screenshots of what the task would look like, and participants read them at their own pace. The instructions were as follows (translated from French):

"As a reminder, at the beginning of this experiment, you performed two tasks. In response to a word (for example, "jewelry"), you were required to give two types of responses: the first response that comes to your mind (for example, "jewelry-necklace") and an unusual but understandable response (for example, "jewelry-money"). Similar to the previous task, with each new trial, you will see a word at the top of the screen (for example, "jewelry"), but this time it will be associated with two other proposals (for example, "necklace" and "money"). Choose the association you prefer: "jewelry" with "necklace" or "jewelry" with "money." In other words, would you have preferred to respond with "necklace" or "money" to the word "jewelry" in the second task (unusual response)? To select a response, use your index finger (left response) or your middle finger (right response). You do not need to validate your choice; it will be framed and validated as soon as you press. Another trial will then start."

3. *Supplementary figures and tables*

Supplementary figures and tables mentioned in the main text are depicted below.

Individuals prefer responses that are both adequate and original: post-hoc analyses on the alpha parameter.

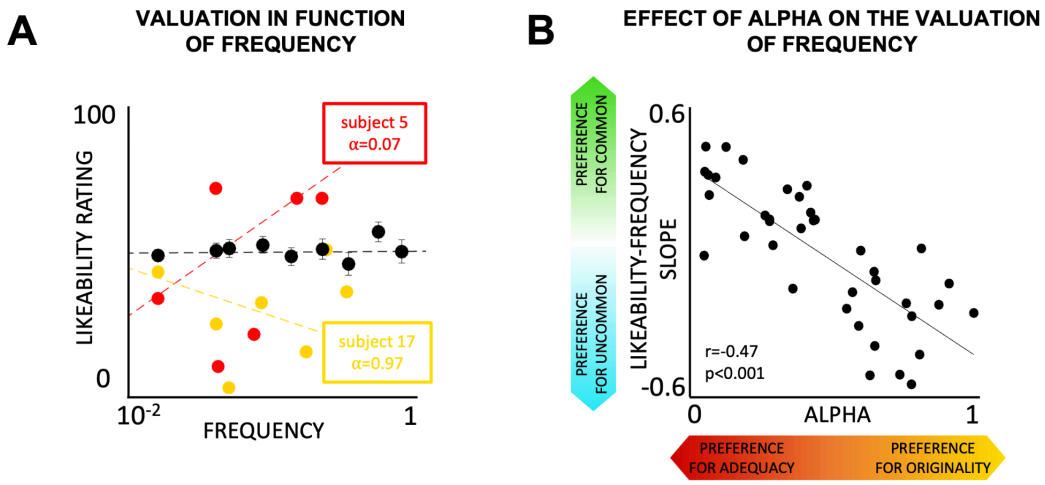

Figure S1: Link between valuation of frequency and preference for originality. (A) Correlation between likeability ratings and frequency of associations. Black circles are bins of averaged participant data. Error bars are intersubject standard error of the mean (SEM). The dashed black line indicates a non-significant linear regression fit at the group level ($p>0.05$). To illustrate intersubject variability, the red and yellow circles and dashed lines are data points and linear regressions for two subjects showing respectively a strong preference for adequacy ($\alpha<0.05$) and originality ($\alpha>0.05$). **(B)** Correlation between the likeability-frequency slope of panel A and the preference for originality (α). Each circle represents one participant. The solid line indicates a significant correlation at the group level ($p<0.05$).

Comparing the functional localizer of originality and adequacy evaluation to atlas functional networks : all common voxel counts

	likeability ratings	originality ratings	adequacy ratings	BVS	ECN	DMN	visual	somatomotor	dorsal attention	salience	limbic
likeability ratings	120078										
originality ratings	37419	236590									
adequacy ratings	26709	150112	150112								
BVS	**33369**	35543	7000	126725							
ECN (ECN excluding BVS)	4417 (4350)	17682 (17650)	**59921** (58713)	4082	207034						
DMN (DMN excluding BVS)	27718 (19630)	**82262** (77092)	24227 (22363)	17530	4082	248106					
visual	17615	23842	3769	0	0	0	150346				
somatomotor	767	0	2527	0	0	0	0	138244			
dorsal attention	2282	13346	14748	0	0	0	0	0	122876		
salience	2255	11357	5747	6252	0	0	0	0	0	131520	
limbic	10168	19756	4569	14072	0	0	0	0	0	0	90979

Table S1: Common voxels in functional networks of interest. Number of common voxels between the networks of Yeo et al.'s atlas (52) and the statistical maps of the parametric modulation of the likeability rating task by likeability, originality and adequacy ratings. Numbers in parentheses correspond to the voxel count of the overlap of ECN and DMN networks with BVS regions, which were removed from the DMN and ECN ROIs in the following analyses. Only the results in bold are reported in the main text.

Locating the neural encoding of likeability during idea production: control analyses of response times neural correlates

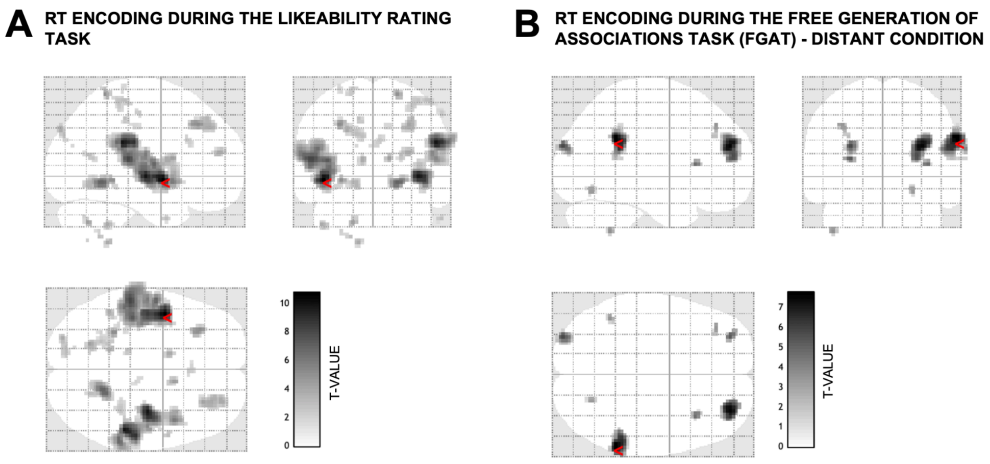

Figure S2: Neuroimaging results of response times correlates during the likeability rating task and the FGAT-distant. (A) Neural correlates of RT during the likeability rating task. **(B)** Neural correlates of RT during the FGAT-distant. Shades of grey indicate the T-statistic of one-sample t-tests, FWE $p<0.05$. Red arrows indicate the global maximum. See Table S2 for all significant clusters. Neural correlates do not overlap with the BVS.

task						parametric modulator		
likeability rating task						**response time during the likeability rating task**		
cluster label	cluster size	peak side	x	y	z	Z-score	T-value	cluster p-value
insula/superior temporal gyrus	**1248**	**L**	**-44**	**0**	**-4**	**7.18**	**10.71**	**<10-16**
insula/superior temporal gyrus	417	R	36	-15	-2	6.94	10.06	<10-16
supramarginal gyrus/superior temporal gyrus	**588**	**R**	**52**	**-35**	**26**	**6.92**	**10.00**	**<10-16**
lingual gyrus	111	R	19	-52	-7	6.22	8.35	1.10-8
middle frontal gyrus	45	L	-31	30	40	5.78	7.44	1.10-5
lingual gyrus	83	L	-28	-42	-4	5.74	7.35	1.10-7
superior parietal lobule	13	R	19	-50	66	5.70	7.28	0.001
cerebellum	17	L	-18	-65	-40	5.57	7.04	6.10-4
caudate nucleus	21	R	12	8	13	5.54	6.97	3.10-4
middle frontal gyrus	87	R	29	32	40	5.51	6.92	1.10-7
superior frontal gyrus	33	R	29	48	18	5.44	6.79	5.10-5
cerebellum	14	L	-14	-48	-57	5.41	6.74	0.001
caudate nucleus	20	L	-11	2	13	5.40	6.73	3.10-4
occipital cortex	47	L	-24	-88	36	5.40	6.73	9.10-6
cerebellum	19	L	-46	-48	-42	5.39	6.71	5.10-4
postcentral gyrus (S1)	56	R	46	-32	60	5.22	6.40	3.10-6
calcarine sulcus	16	R	22	-65	16	5.20	6.37	0.001
inferior temporal gyrus	6	R	56	2	-37	5.16	6.30	0.006
cerebellum	9	L	-21	-55	-52	5.14	6.27	0.003
midcingulate cortex	8	L	-14	-32	46	5.13	6.25	0.004
superior parietal lobule/postcentral gyrus (S1)	14	L	-18	-50	70	5.11	6.21	0.001
anterior cingulate cortex	16	R	4	20	28	5.07	6.15	0.001
postcentral gyrus (S1)	8	R	56	-20	50	5.05	6.12	0.004
cerebellum	1	L	-11	-65	-54	4.96	5.96	0.026
midcingulate cortex	9	R	12	-25	38	4.89	5.84	0.003
postcentral gyrus (S1)	8	L	-31	-35	70	4.88	5.83	0.004
rolandic operculum	3	R	52	-5	8	4.84	5.76	0.013
occipital cortex	1	L	-16	-78	23	4.82	5.74	0.026
task						parametric modulator		
FGAT-distant						**response time during the FGAT-distant**		
cluster label	cluster size	peak side	x	y	z	Z-score	T-value	cluster p-value
supramarginal gyrus/superior temporal gyrus	**237**	**R**	**62**	**-48**	**28**	**5.92**	**7.71**	**5.10-11**
lateral frontal pole	**216**	**R**	**32**	**50**	**23**	**5.86**	**7.59**	**2.10-10**
superior frontal gyrus/middle frontal gyrus	56	L	-28	-92	23	5.52	6.94	1.10-4
occipital cortex	21	L	-28	50	13	5.45	6.82	0.009
superior frontal gyrus/middle frontal gyrus	13	R	36	20	8	5.34	6.62	0.033
insula/inferior frontal gyrus	14	L	-44	-52	-47	5.15	6.29	0.028
cerebellum	14	L	-36	38	40	5.13	6.25	0.028
fuisform gyrus/lingual gyrus	16	R	24	-68	-14	5.10	6.20	0.020

Table S2: All clusters in the SPMs of the parametric modulation analyses of the likeability rating task and the FGAT-distant by response times. p-values are FWE corrected. Coordinates x, y and z refer to the Montreal Neurological Institute space. Only the results in bold are reported in the Supplementary Results.

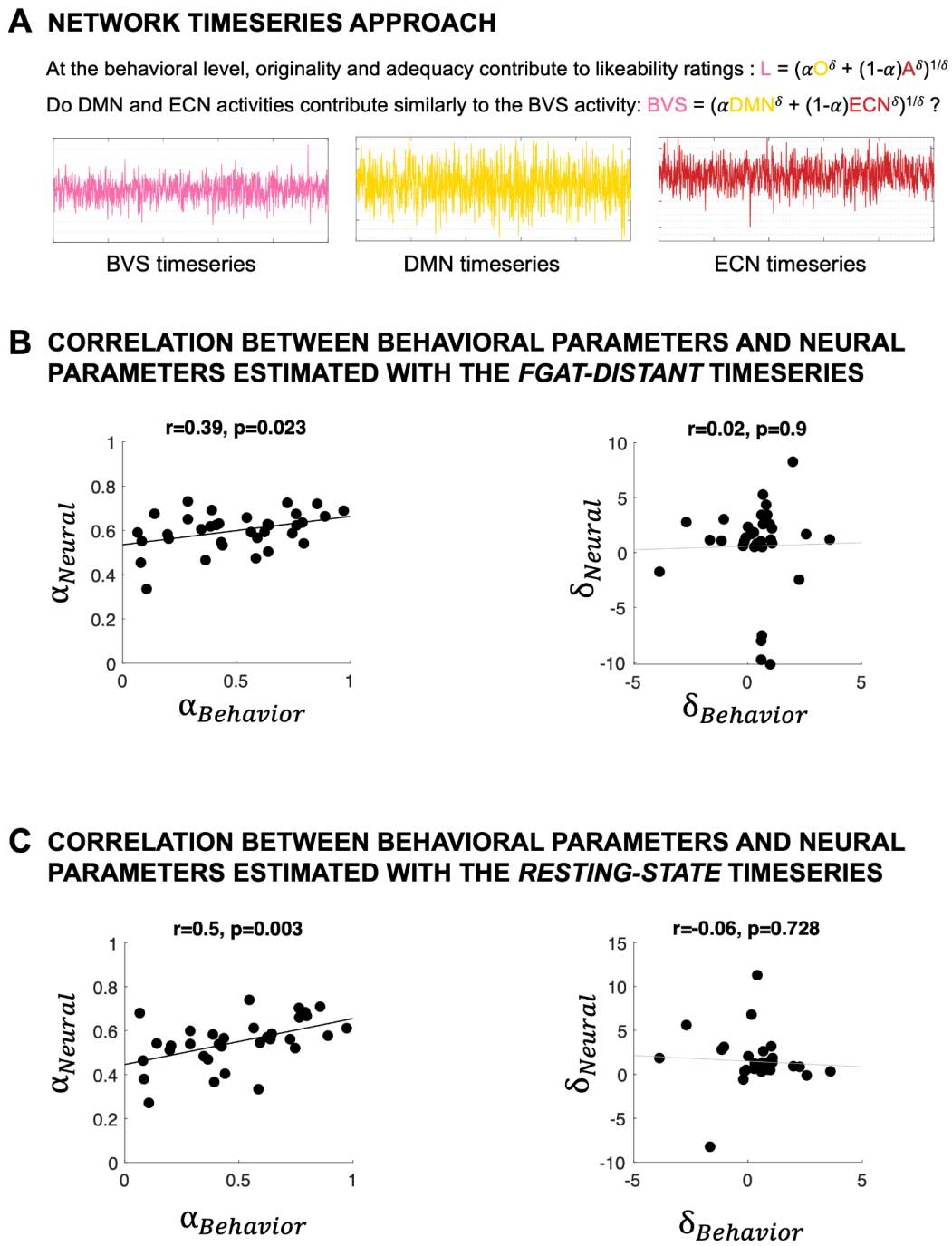

Figure S3: Correlation between the parameters of the CES, estimated with behavioral and neural data. (A) Schematics of the analysis approach. The timeseries depicted here for illustration purposes are simulated data. **(B)** Correlation between the behavioral parameters and the neural parameters estimated using the FGAT-distant timeseries. **(C)** Correlation between the behavioral parameters and the neural parameters estimated using the resting-state timeseries. $\alpha_{behavioral}$ and $\delta_{behavioral}$ were estimated using the CES model fitted on the likeability, originality and adequacy ratings. α_{neural} and δ_{neural} were estimated using the CES model fitted on BVS, DMN and ECN timeseries during the FGAT-distant task (B) or during the resting-state (C). Each dot represents one participant. Black lines indicate significant correlations ($p<0.05$), and grey lines indicate non-significant correlations ($p>0.05$).