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The Beholder's Share: Bridging art and neuroscience to study individual differences in subjective experience

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Our experience of the world is inherently subjective, shaped by individual history, knowledge, and perspective. Art offers a framework within which this subjectivity is practiced and promoted, inviting viewers to engage in interpretation. According to art theory, different forms of art—ranging from the representational to the abstract—challenge these interpretive processes in different ways. Yet, much remains unknown about how art is subjectively interpreted. In this study, we sought to elucidate the neural and cognitive mechanisms that underlie the subjective interpretation of art. Using brain imaging and written descriptions, we quantified individual variability in responses to paintings by the same artists, contrasting figurative and abstract paintings. Our findings revealed that abstract art elicited greater interindividual variability in activity within higher-order, associative brain areas, particularly those comprising the default-mode network. By contrast, no such differences were found in early visual areas, suggesting that subjective variability arises from higher cognitive processes rather than differences in sensory processing. These findings provide insight into how the brain engages with and perceives different forms of art and imbues it with subjective interpretation.

individual differences | aesthetics | Beholder's Share

Significance

The Beholder's Share in art history posits that a work of art is completed by the viewer, who infuses it with personal meaning. Here, we present an empirical examination of a key assumption of the Beholder's Share: that abstract art elicits more subjective interpretation than representational art due to its inherent ambiguity. To investigate this, we quantified interindividual differences in brain activity in response to abstract or representational paintings. Our findings revealed more person-specific responses to abstract paintings, indicating that individuals contribute more personal associations to abstract art than to representational art. These unique patterns were observed in brain regions associated with internally-oriented cognition rather than areas involved in visual perception, providing empirical evidence supporting the Beholder's Share.

Our experience of the world is subjective, shaped by the constant process of interpretation. Art plays a unique role in revealing this subjectivity, not only by expressing the artist's distinct vision but also by inviting the viewer to actively engage in the construction of meaning. Unlike other forms of visual processing, which often adhere to normative interpretations, the experience of viewing art demands that the observer take on a creative, interpretive role (1, 2). This dynamic interaction between the artwork and the viewer has been described by art theorists as the Beholder's Share.

The concept of the Beholder's Share provides a framework for understanding subjective experience through the lens of art. In this view, the viewer is not simply a passive recipient of visual sensations but an active participant who brings their unique perceptual, conceptual, and emotional experience to the work of art (1–4). Different forms of art engage these prior experiences in different ways. Figurative (representational) art, with its grounding in recognizable forms and shared representations, provides a common framework for viewers. In contrast, abstract (nonrepresentational) art, which avoids familiar depictions of objects and scenes, invites the observer to project personal memories, associations, and meanings, amplifying the role of individual interpretation.

Despite the intuitive appeal of this theory, only very few studies have evaluated it empirically. In prior behavioral research, we found that abstract art appears to shift viewers toward a more internally-oriented mindset, consistent with the theoretical predictions of the Beholder's Share (5). In this study, we seek to extend this understanding by examining the neural underpinnings of this phenomenon. Specifically, we seek to identify patterns of brain activity corresponding to the Beholder's Share and to understand how they vary across individuals, reflecting the diversity of experience elicited by different forms of art.

Research in neuroaesthetics has revealed much about how art is processed visually and how art evokes preferences and attribution of value (6–8). However, most studies so far have focused on shared responses to different categories of stimuli, averaged across participants and over paintings (9–11). Therefore, there has been a lack of empirical data addressing the question of how, and whether, abstract art elicits more variable neural responses and whether such variability in the brain relates to viewers' subjective experience. The Beholder's Share suggests that we bring our own associations and memories to an abstract painting; if so, our responses should be subject-unique and should lead to individual variability across participants in neural responses to the same painting. Multivariate data analysis techniques that look at shared and idiosyncratic response patterns across participants (12–17) offer an analytical approach towards an empirical test of the Beholder's

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Share. Here, we exploit this approach to provide an empirical test of how participants vary in their responses to art, directly addressing the notion of variability in subjective experience, which is at the very core of the Beholder's Share.

This study addresses two main questions about the Beholder's Share: 1) Does abstract art evoke more subjective interpretations, and 2) Where in the hierarchy of sensory to mnemonic processes does this occur in the brain? To address the first question, we collected written captions that participants produced in response to viewing abstract and figurative paintings by the same artist. Figurative paintings depicted a recognizable object, person, or scene; abstract paintings depicted no recognizable objects. We then quantified the cross-subject variation in semantic meaning.

To address the second question, we presented a different sample of healthy human participants with the same abstract and figurative paintings while they were scanned with fMRI. We then quantified patterns of Blood-Oxygen-Level Dependent (BOLD) response that varied across participants in response to the same painting, thus mirroring the processes of subjective interpretation that are theorized by the Beholder's Share. Based on previous work (5), we predicted that abstract art, compared to figurative art, would evoke more internally-oriented thoughts and therefore would be associated with activation in brain areas known to be involved in internally-oriented processing, such as the Default Mode Network (DMN). The DMN has been implicated in self-referential processes, such as autobiographical memory (18, 19) and narrative interpretation (15, 17, 20), as well as in aesthetic experiences, where DMN activity has been associated with the subjective experience of being "moved" by art (21, 22). However, the role of the DMN in the Beholder's Share, and in response to abstract versus figurative art, has not been examined.

Results

Individual Variability in Semantic Interpretations of Abstract Paintings. We first tested whether people respond more variably to an abstract painting than to a figurative painting when asked to freely generate a written description of the painting. We collected captions of each painting (164 in total) from an online sample of 30 participants (Fig. 1*B*). For each painting, we calculated the cross-subject dissimilarity in semantic meaning of captions (*SI Appendix*, Fig. S3). We then regressed this dissimilarity measure onto the level of abstraction of the painting, obtained by an independent sample of participants (*SI Appendix*). We found that semantic dissimilarity of captions varies with level of abstraction of the painting (Fig. 3*B*). This suggests that abstract art elicits differences in verbalizable interpretation across participants.

Dissimilarity in Patterns of BOLD Response: Neural Evidence of the Beholder's Share. We presented 29 healthy human participants with abstract and figurative paintings while they were scanned with fMRI and asked them to make subjective decisions about each painting (Fig. 1*B*), using a previously developed task taken from (5) (*SI Appendix*). We reasoned that abstract art would elicit more individual contribution and that this would manifest in greater cross-subject dissimilarity in BOLD responses.

To measure whether abstract art elicits more dissimilarity in brain activity, we obtained a "whole brain dissimilarity measure." We divided each participant's brain into anatomical parcels (using the Harvard-Oxford Atlas) and extracted the BOLD time series for all regions. For each painting, we computed the dissimilarity in regional activations across participants. We found that whole-brain patterns of responses differed across participants significantly more for abstract paintings than for figurative paintings ($t(162) = 5.34$, $P < 0.001$) (Fig. 3*A*). To test the sensitivity of these differences to the level of abstraction, we determined average abstraction ratings for each painting and tested whether these subjective measures of abstraction correlated with the dissimilarity values in BOLD activity. We found that indeed the paintings with higher perceived levels of abstraction were associated with greater dissimilarity ($r = 0.32$, $P < 0.001$) (Fig. 3*A*). These results indicate that abstract art yields more variable responses than figurative art, substantiating a basic assumption of the Beholder's Share.

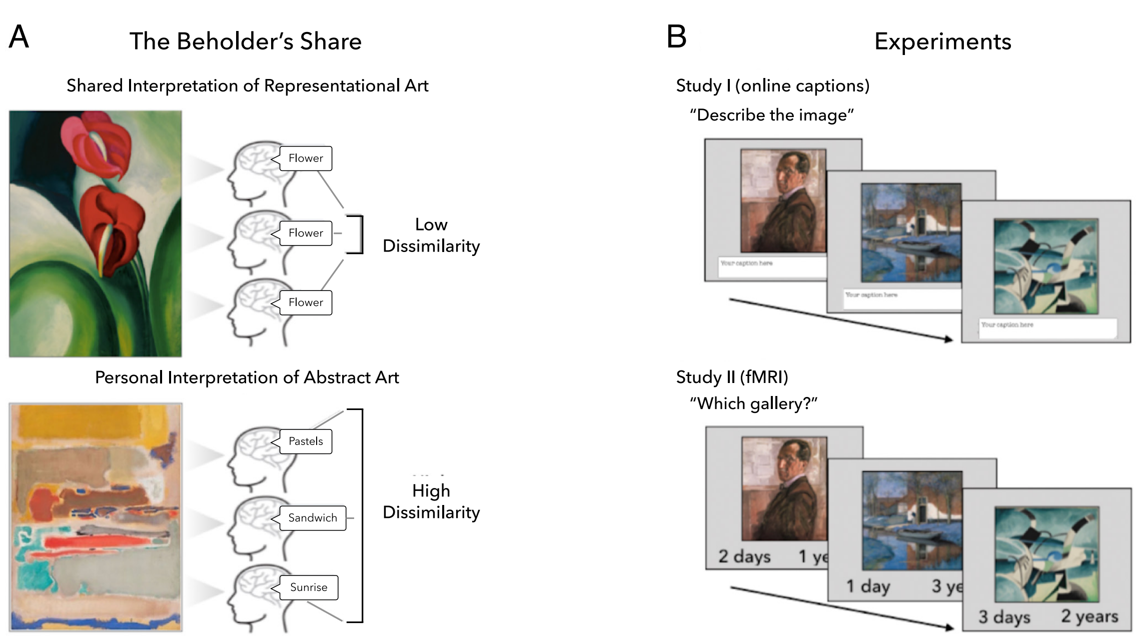

Fig. 1. The Beholder's Share and Task Design. (*A*) The Beholder's Share as Variability in Responses across Subjects. To quantify the Beholder's Share, we measured dissimilarity in brain responses across subjects to each individual painting. We predicted that abstract paintings would elicit individual interpretations, which would manifest in higher cross-subject dissimilarity in brain responses and written descriptions. (*B*) Tasks. Captions study (*Top*): In a behavioral study, an independent group of participants was asked to describe paintings in 280 characters or less. fMRI study (*Bottom*): In an fMRI scanner, subjects viewed abstract and figurative paintings one at a time and were asked to sort each into a gallery opening in the next few days or a gallery opening in the next few years.

The Beholder's Share Emerges in Higher Level Cognitive Areas. Following the whole-brain analyses, we additionally sought to determine where in the brain does this variability arise? More specifically, do these dissimilar neural representations arise in regions responsible for early processing of incoming visual stimuli or in regions responsible for more internally-driven cognitive processes? While figurative art guides one through the scene, abstract art allows for more freedom to look around the painting. This could lead to differences in incoming visual information. If this were the case, we would expect abstract art to generate increased variability in patterns of BOLD response in early visual regions. Alternatively, abstract paintings may allow people to draw on unique internal representations, rather than differences in visual processing related to different incoming visual information. If so, we should see variability in brain regions responsible for more internally-driven cognitive processes. One strong candidate for a network of structures is the DMN, which is implicated in tasks that require drawing on internally-constructed information such as autobiographical memory (23), abstract thought (24, 25), and narrative interpretation (17, 20).

We computed voxel-wise cross-subject dissimilarity in individual regions-of-interest (Fig. 2) consisting of core nodes of the DMN, specifically the precuneus (PC) and the FMC, as well as regions involved in early visual processing–the occipital pole, the intracalcarine cortex (ICC), and the supracalcarine cortex (SCC). We found that cross-subject patterns of BOLD responses were more dissimilar across participants for abstract than figurative art in regions overlapping with the DMN (Fig. 3*B*), suggesting that participants are drawing on unique internal representations when experiencing abstract art. We did not find differences in variability between abstract art and figurative paintings in early visual regions, suggesting that the intake of low-level visual information is similar across participants (Fig. 3*B*). Together, the findings that cross-subject patterns of BOLD responses are more dissimilar across-participants for abstract than figurative art in regions of the DMN, but not in early visual regions, suggests that abstract art may evoke similar visual sensations across participants, but different interpretations.

Control Analyses. We then conducted a number of control analyses to explore the boundaries of these effects and their selectivity.

Controlling for differences in activation. Cross-subject dissimilarity could be caused by measurement noise, which could play a larger role for stimuli that evoke smaller responses in a brain region. To control for differences in activation across paintings, we modeled each region with a linear regression that predicted the dissimilarity of each painting from the painting's abstraction value, controlling for each painting's average BOLD response in the region. We found that even when controlling for activation in the region, the PC (b = 0.015, sd = 0.004, P < 0.001) and FMC (b = 0.005, sd = 0.002, P < 0.01) show higher cross-subject dissimilarity for more abstract paintings, while early visual regions did not show differences in cross-subject dissimilarity between abstract and figurative art. We also found a significant interaction between the occipital pole and PC and not between the occipital pole and the FMC (*SI Appendix*, Table S1). A comprehensive analysis of the relationship between activation and dissimilarity in each region is shown in *SI Appendix*, Fig. S5.

Controlling for differences in visual statistics of paintings. To rule out that these differences in neural dissimilarity are due to differences in low-level visual features between abstract and figurative art, we computed the means and SD for a set of visual statistics of the paintings (entropy, brightness, saturation, SD of hue, SD of brightness, and SD of saturation). We found that these low-level visual statistics do not significantly differ between abstract and figurative art (*SI Appendix*, Fig. S1) and none of these features predict dissimilarity (*SI Appendix*, Fig. S4).

Validation of dissimilarity measure with behavior. We sought to determine whether variation in neural activity could be explained by individual differences in liking of abstract paintings. To address this question, we compared cross-subject dissimilarity in liking ratings for each painting with differences in neural activation. Specifically, we constructed subject-by-subject RDMs based on the absolute distance between participants' liking ratings. These liking RDMs were then correlated with subject-by-subject RDMs derived from patterns of BOLD activity in the brain regions we had previously tested.

Our analysis revealed significant correlations between liking distance and dissimilarity in neural activation in the FMC [overlapping with ventral medial prefrontal cortex (vmPFC)] and the anterior temporal lobe. The vmPFC is well known for its role in subjective value representation and has recently been implicated in the subjective valuation of art (7). The finding that individual variability in liking is reflected in patterns of BOLD activity in the vmPFC suggests that this measure captures a meaningful component of the subjective experience of art, rather than random noise. Notably, the lack of similar correlations in other regions indicates that participants' neural responses to art reflect dimensions of experience beyond simple liking (*SI Appendix*, Fig. S7). These results underscore the complexity of art appreciation, highlighting that while subjective valuation is a significant factor, it represents just one facet of the broader, multidimensional experience elicited by abstract art.

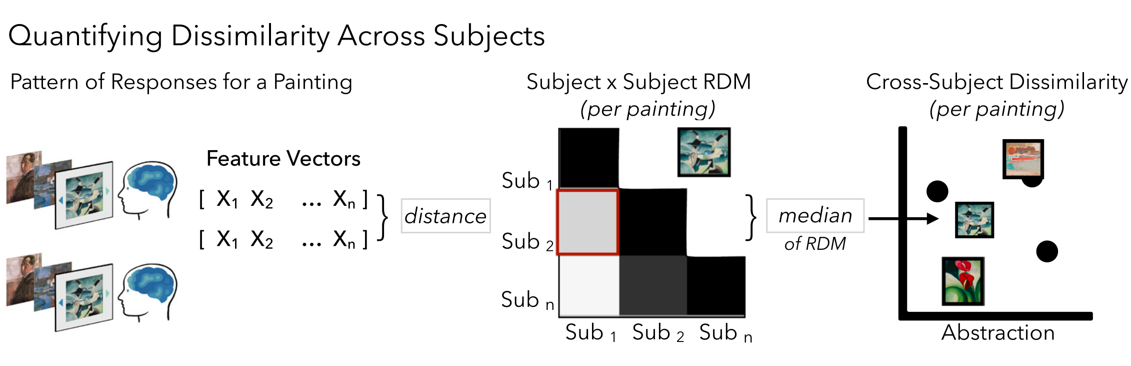

Fig. 2. Computing Cross-subject Dissimilarity per Painting. We measured cross-subject dissimilarity in responses to each painting individually. To do this, we extracted feature vectors from each subject's responses (whether semantic features or patterns of BOLD activation). We then computed the dissimilarity between each subject's pattern of activity for each painting, resulting in a subject x subject Representational Dissimilarity Matrix (RDM) for each painting. We then take the median of this matrix as our cross-subject dissimilarity measure for each painting. Finally, we correlate each painting's dissimilarity value with its abstraction rating (obtained from an independent set of subjects).

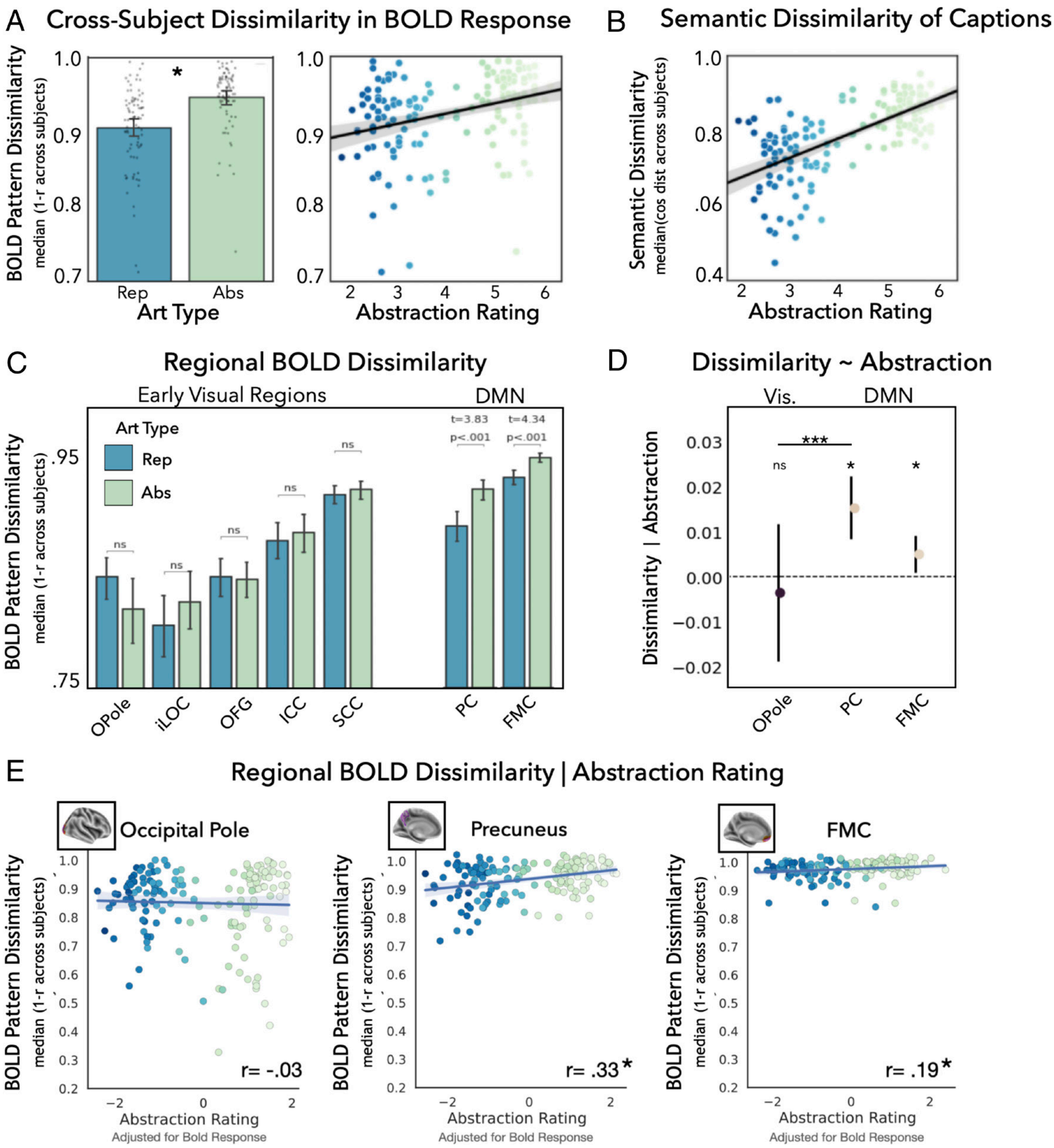

Fig. 3. Neural Dissimilarity in Responses to Abstract and Figurative Art. (*A*) Cross-subject Dissimilarity in Whole Brain BOLD response. We computed cross-subject correlations on the pattern of average activation of all regions in the Harvard Oxford atlas. For each painting, we computed a subject x subject correlation matrix and extracted the median correlation from that matrix. (*Left*) The cross-subject dissimilarity value for each of 164 paintings, grouped by art type. Abstract paintings elicit more cross-subject variability in brain activation than to figurative paintings. (*Right*) The same cross-subject dissimilarity value, plotted according to each painting's average abstraction rating. We find a significant correlation between abstraction of a painting and dissimilarity in BOLD response. (*B*). Semantic Dissimilarity. Cross-subject dissimilarity for semantic content of captions for each painting. Semantic Dissimilarity was calculated as the median cosine distance between all caption embeddings for each painting. Each data point represents a painting. Dissimilarity increases with the abstraction level of the painting. (*C*). Regional Bold Dissimilarity. Cross-subject dissimilarity for abstract and figurative paintings from selected visual regions and regions of the DMN. Opole=Occipital pole; iLOC=inferior Lateral Occipital Cortex; OFG=Occipital Fusiform Gyrus; ICC=Intracalcarine Cortex; SCC=Supracalcarine Cortex; PC=Precuneus; FMC=Frontal Medial Cortex. We find that abstract paintings elicit higher cross-dissimilarity in DMN regions than figurative art, but not in early visual regions. (*D*). Model Predicting Dissimilarity of a Painting from its Abstraction Level. Coefficients from a linear regression model regressing abstraction level of each painting onto its dissimilarity value, controlling for magnitude of activation. Higher values indicate higher dissimilarity for more abstract paintings. *P*-values were obtained from comparing a model including abstraction rating as a predictor to a null model (model excluding abstraction rating). * indicates regions with significant ($q < 0.05$) relationship between abstraction and cross-subject dissimilarity, corrected for multiple comparisons using FDR correction. Abstract paintings elicit more cross-subject dissimilarity than figurative paintings in the DMN and not in the early visual cortex. (*E*) Correlation Between Abstraction Rating and Dissimilarity. Visualization of computed semipartial correlations between abstraction rating and BOLD pattern dissimilarity in the Occipital Pole, Precuneus, and FMC. The x-axis represents the average abstraction rating of a painting, from which the average BOLD response has been partialed out.

Discussion

Understanding how the human brain constructs subjective experiences provides a profound insight into the intersection of neuroscience, psychology, and the humanities. Art, in particular, offers a unique lens through which to examine this interplay. A pivotal concept in this realm is the Beholder's Share, which captures the active role of the viewer in interpreting and ascribing meaning to art (1–4). Rooted in the viewer's own history, knowledge, and expectations, this phenomenon becomes especially pronounced when encountering abstract art, where the absence of clear representational content invites greater projection and personal interpretation.

In our study, we sought to empirically test a central tenet of the Beholder's Share: that an individual's experience of a work of art is shaped by their own personal context and prior experience, especially when viewing abstract (nonrepresentational) art compared to figurative (representational) art. We tested this idea by comparing variability in responses to abstract and figurative paintings by the same artist and found that participants exhibited greater variability in their reactions to abstract art. This variability manifested both in verbal descriptions and in brain activity. Interestingly, cross-participant differences in brain activation were observed in the DMN, rather than in primary visual areas, suggesting that the individualized nature of abstract art experiences arises from higher-order cognitive processes rather than differences in early visual processing.

The DMN has long been associated with self-referential and internally-generated processes, including narrative interpretation (15, 20) and sense-making (26) as well as autobiographical memory, prospection, creativity, and imagination (24, 25, 27). Our findings align with these roles, suggesting that the DMN supports the interpretative and sense-making processes central to engaging with abstract art. These observations also build on prior research showing that the DMN is active during aesthetic experiences and can reflect shared or divergent interpretations across participants, depending on their personal experiences and construction of meaning (13, 20, 21).

The variability observed in our study invites several intriguing questions about the cognitive and emotional underpinnings of the Beholder's Share. For instance, do differences in interpretive responses reflect variability in individuals' capacity to generate representational content from ambiguous stimuli? Might they instead stem from differences in emotional resonance or aesthetic taste? Future research should aim to disentangle these factors systematically, potentially illuminating broader principles of how the brain constructs meaning from ambiguity.

The Beholder's Share can be conceptualized as the influence of priors on interpretation of an image. In this study, we did not attempt to manipulate those priors and, instead, participants were left to engage in the process of interpretation on their own. Prior research, however, demonstrates that exposure to specific perceptual, semantic, or emotional stimuli can bias the interpretation of ambiguous images (28, 29). Future work could build on this foundation, systematically exploring how priming shapes responses to abstract art, constraining interpretation through targeted exposure.

In addition, while there may be many reasons why people have different priors that they bring to bear when interpreting abstract art, previous work suggests that one's personality (e.g., openness to experience), former experience with art, and emotional/affective biases may be especially important factors (30–32). These factors have been shown to affect different emotional responses to art (33–36) and future work could consider these factors as sources of variability in response.

Another dimension of variability lies in the processes individuals engage in when interpreting abstract art. While some people may resolve ambiguity relatively easily, others may require more time, reflecting differences in the cognitive mechanisms of interpretation. Ambiguity resolution often involves evidence accumulation—a process well documented in decision-making tasks involving both simple perceptual inputs and complex value-based judgments (37–39). More ambiguous input requires more evidence for its resolution and therefore takes more time (40). One possibility therefore is that the process of evidence accumulation may vary across people. Testing these dynamics in the context of art perception could yield insights into how humans navigate and resolve ambiguity in complex, subjective domains.

Implications for Both Fields of Art and Neuroscience. Our interdisciplinary study bridges neuroscience and art, leveraging abstract and figurative paintings to probe the subjective nature of human experience. By applying multivariate neuroimaging analyses, we uncover differences in individual responses to art, advancing the burgeoning field of neuroaesthetics. Our findings provide empirical support for a concept that has shaped art theory for over a century—the Beholder's Share. Importantly, this work positions art as a potent tool for understanding the mind, offering a naturalistic means of eliciting and studying subjective experience.

Neuroscientists are increasingly recognizing the value of investigating individual differences in perception and cognition (14, 41–43). Art, with its multidimensional and inherently personal nature, serves as a uniquely effective stimulus for exploring these differences. Understanding variability may be particularly relevant for studying populations characterized by heightened cross-subject differences, such as clinical groups and adolescents (44)—populations often deemed "noisier." Art's capacity to evoke individualized responses may provide a valuable framework for investigating heterogeneity in these populations, adding to existing efforts (45–47) and refining predictive models for treatment outcomes.

In a broader sense, the study of art allows us to interrogate the subjective dimensions of human cognition that are often overlooked in efforts to identify shared neural and behavioral patterns. The Beholder's Share encapsulates this individuality and provides a framework within which to explore how personal history, context, and intrinsic traits shape perception. By systematically studying responses to works of art that differ in their capacity to evoke subjective interpretation, we begin to characterize the unique nature of our human experience.

Materials and Methods

Study 1: Captions.

Stimuli. Participants saw 164 paintings that were either representational or abstract (82 per category). Representational paintings depicted a recognizable object, person, or scene; abstract paintings depicted no recognizable objects. Paintings were chosen from abstract expressionist artists, who had been representational painters early in their careers. Thus, we were able to use representational and abstract paintings from the same artist, balancing across categories visual features associated with the artist's style (*SI Appendix*, Fig. S1).

Captions task. To quantify differences in semantic responses to paintings, we asked an independent sample of 30 MTurk participants to describe each painting as "one would for a friend" in 280 characters or less (Fig. 1*B*). Participants were given no time limit and were not restricted to native English speakers. MTurk participants were restricted to those with a 90% approval rating or above. Captions were verified for relevance (i.e., participants did not copy and paste an irrelevant phrase across all paintings). All procedures were preapproved by Columbia University's Institutional Review Board and all participants consented.

Independent abstraction ratings. Abstraction ratings of each painting were obtained in a separate set of 10 participants, queried using MTurk. participants saw each painting, one at a time, and rated how abstract the painting was on a scale from 1 to 7. Participants were not restricted to native English speakers, and there was no time limit in the task. Each painting's abstraction rating was first mean-centered by subject and then averaged across all participants for each painting.

Computing semantic dissimilarity of captions. To quantify differences in semantic responses to paintings, we asked an independent set of participants (n = 30) to give a caption for each painting. We then extracted each caption's semantic vector, a numerical representation in semantic space, using the Google Sentence Encoder, a language processing model optimized to encode sentences or short phrases (48). We then computed the cosine distance between each subject's caption, resulting in a subject x subject RDM for each painting. The median of this RDM became the painting's semantic dissimilarity value. We then correlated this dissimilarity value with the perceived abstraction level of each painting, as collected from a different set of participants.

Study 2: fMRI.

Participants. We tested 29 participants from in and around the Columbia area who answered an advertisement from a flier posted around campus or from a recruitment website. Participants were paid $25 dollars per hour. All procedures were preapproved by Columbia University's Institutional Review Board. Informed consent was obtained from all participants.

Stimuli. Participants saw the same stimuli as in the captions task.

fMRI acquisition. MRI data were collected on a 3 T Siemens Magnetom Prisma scanner with a 64-channel head coil. Functional images were acquired using a multiband echo-planer imaging sequence (repetition time = 1.5 s, echo time = 30 ms, flip angle = 65°, acceleration factor = 3, voxel size = 2 mm iso). Sixty nine oblique axial slices (14° transverse to coronal) were acquired in an interleaved order and spaced 2 mm to achieve full brain coverage. Whole-brain high resolution (1 mm iso) T1-weighted structural images were acquired with a magnetization-prepared rapid acquisition gradient-echo sequence. Field maps consisting of 69 oblique axial slices (2 mm isotropic) were collected to aid registration.

Construal-level task. Participants viewed 164 abstract and representational paintings and sorted each into a gallery opening in the near or far future. (*SI Appendix*, Fig. S1). Each subject completed 164 trials equally divided between four runs (41 trials per run). Each trial lasted a total of 6.5 s and consisted of a viewing phase (4 s) and a choice phase (2.5 s). In the modeling below, we considered the full 6.5 s period when measuring neural responses. Each trial was separated by a jittered intertrial interval drawn from an exponential distribution with a mean of 3. If the value generated was below 1 or above 12, it was redrawn. In the viewing phase, a painting appeared on the screen alone for 4 s. Following that, the choice phase began, and answer choices appeared below the painting for 2.5 s, during which the participants were able to make their choice. The answer choices consisted of one near choice and one far choice, randomly presented. The near choice option was randomly drawn from three options: 1 d, 2 d, or 3 d, and the far choice could be either 1 y, 2 y, or 3 y (*SI Appendix*, Fig. S2*B*).

Liking ratings of images (outside of scanner). After completing the construal level task in the scanner, participants were presented with the same images outside of the scanner on a lab computer. They were then asked to rate how much they liked each painting on a scale of 1 to 7. Ratings were then z-scored by subject.

Construal level theory. We imaged participants while looking at abstract and representational art and completing a task designed to drive processes of mental projection. Construal Level Theory has shown a relationship between abstraction and future thought, such that objects or events occurring farther in the future are mentally represented more abstractly, and conversely, more abstract objects and events are thought of as more distant (49). This process of mental distancing that abstraction evokes involves attention to more internal processes and implies a lower reliance on the immediate external environment (*SI Appendix*, Fig. S2*A*). In a previous behavioral experiment, we found that participants are more likely to project abstract art into more distant situations in time or space (5), suggesting that abstract art invokes this distancing process, and potentially, more internally oriented thought.

Behavioral analysis. We used a linear modeling package made for the programming language R: lme4 (50). We ran a mixed effects logistic regression to model the relationship between painting category and psychological distance, while controlling for liking of each painting. Our model included Painting Category and Liking Rating as fixed effects, and by-subject random intercepts with random slopes for the effect of painting category. P-values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question. We confirmed that participants mentally project abstract art farther into the future than representational art (b(representational) = -0.2, CI = [-0.33 to 0.08], $P = 0.002$).

Imaging analysis. Results included in this manuscript come from preprocessing performed using fMRIPprep 1.1.4 which is based on Nipype 1.1.1. Many internal operations of fMRIPrep use Nilearn 0.4.2 mostly within the functional processing workflow.

Anatomical data preprocessing. The T1-weighted (T1w) image was corrected for intensity nonuniformity using N4BiasFieldCorrection (51) (ANTs 2.2.0) and used as T1w reference throughout the workflow. The T1w-reference was then skull-stripped using antsBrainExtraction.sh (ANTs 2.2.0), using OASIS as target template. Brain surfaces were reconstructed using recon-all (52) (FreeSurfer 6.0.1), and the brain mask estimated previously was refined with a custom variation of the method to reconcile ANTs-derived and FreeSurfer derived segmentations of the cortical gray-matter of Mindboggle (53). Spatial normalization to the ICBM 152 Nonlinear Asymmetrical template version 2009c (54) was performed through nonlinear registration with antsRegistration (ANTs 2.2.0) (55), using brain-extracted versions of both T1w volume and template. Brain tissue segmentation of cerebrospinal fluid (CSF), white matter (WM), and gray matter (GM) was performed on the brain-extracted T1w using fast (FSL 5.0.9) (56).

Functional data preprocessing. For each of the 4 BOLD runs found per subject (across all tasks and sessions), the following preprocessing was performed. First, a reference volume and its skull-stripped version were generated using a custom methodology of fMRIPrep. Head-motion parameters with respect to the BOLD reference (transformation matrices, and six corresponding rotation and translation parameters) are estimated before any spatiotemporal filtering using mcflirt (FSL 5.0.9) (57, 58). BOLD runs were slice-time corrected using 3dTshift from AFNI. The BOLD time-series (including slice-timing correction when applied) were resampled onto their original, native space by applying a single, composite transform to correct for head-motion and susceptibility distortions. These resampled BOLD time-series will be referred to as preprocessed BOLD in original space, or just preprocessed BOLD. The BOLD reference was then coregistered to the T1w reference using bbregister (FreeSurfer) which implements boundary-based registration (59). Coregistration was configured with nine degrees of freedom to account for distortions remaining in the BOLD reference. The BOLD time-series were resampled to surfaces on the following spaces: fsaverage5. The BOLD time-series were resampled to MNI152NLin2009cAsym standard space, generating a preprocessed BOLD run in MNI152NLin2009cAsym space. Several confounding time-series were calculated based on the preprocessed BOLD: framewise displacement (FD), DVARS, and three region-wise global signals. FD and DVARS are calculated for each functional run, both using their implementations in Nipype, following the definitions by (60). The three global signals are extracted within the CSF, the WM, and the whole-brain masks. Additionally, a set of physiological regressors were extracted to allow for component-based noise correction (CompCor) (61). Principal components are estimated after high-pass filtering the preprocessed BOLD time-series (using a discrete cosine filter with 128 s cut-off) for the two CompCor variants: temporal (tCompCor) and anatomical (aCompCor). Six tCompCor components are then calculated from the top 5% variable voxels within a mask covering the subcortical regions. This subcortical mask is obtained by heavily eroding the brain mask, which ensures that it does not include cortical GM regions. For aCompCor, six components are calculated within the intersection of the aforementioned mask and the union of CSF and WM masks calculated in T1w space, after their projection to the native space of each functional run (using the inverse BOLD-to-T1w transformation). The head-motion estimates calculated in the correction step were also placed within the corresponding confounds file. All resamplings can be performed with a single interpolation step by composing all the pertinent transformations (i.e., head-motion transform matrices, susceptibility distortion correction when available, and coregistrations to anatomical and template spaces). Gridded (volumetric) resamplings were performed using antsApplyTransforms (ANTs), configured with Lanczos interpolation to minimize the smoothing effects of other kernels (62). Nongridded (surface) resamplings were performed using mri_vol2surf (FreeSurfer).

Univariate analysis.

Predetermined contrasts. We conducted a generalized linear model (GLM) analysis on the art distance task data. The first model had the following regressors of interest: 1) The onsets of abstract paintings 2) the onsets of representational paintings. To account for changes in BOLD activity due to reaction time, we also included the same onsets and duration of each trial parametrically modulated by reaction time (which was mean-centered by run). We also included the onsets of missed trials as an additional regressor. Duration for each trial was 6.5 s.

GLM model estimation and correction for multiple comparisons. All GLM models were estimated using FSL's FEAT. The first-level time-series GLM analysis was performed for each run per participant using FSL's FILM. The first-level contrast images were then combined across runs per participant using fixed effects. The group-level analysis was performed using FSL's mixed effects modeling tool FLAME1. Group-level maps were corrected to control the familywise error rate in one of two ways: For whole-brain correction, we used cluster-based Gaussian random field correction for multiple comparisons, with an uncorrected cluster-forming threshold of $z = 2.3$ and corrected extent threshold of $P < 0.05$.

BOLD cross-subject dissimilarity.

Signal Extracted. For each subject, we extracted the BOLD time series using Nilearn's transform function. This function regresses out confounds obtained from fMRI prep and z-scores the signal across each run. We shifted our stimulus labels by 4.5 s to account for hemodynamic lag. The BOLD response to a specific painting was the average BOLD response across all timepoints that the specific painting was on the screen.

Whole brain dissimilarity. We measured cross-subject dissimilarity in brain responses to each painting individually. To get a whole brain dissimilarity measure, we extracted the BOLD time series for each subject and each run using NiftiMasker, which parcels the brain into regions from the Harvard Oxford Atlas, and extracts an average signal across voxels from each region (14). For each painting, we averaged the activity in each parcel across the timepoints that painting was on the screen for each subject. These average activations create a pattern of activity across the brain for each subject in response to an individual painting. We then computed the dissimilarity (1-Pearson's r) between each subject's pattern of activity for each painting, resulting in a subject x subject RDM for each painting. We then took the median of this matrix as our cross-subject dissimilarity measure for each painting. Finally, we compared the distribution of dissimilarities for abstract paintings with the distribution of dissimilarities for representational paintings, using an independent-samples *t* test. We also correlated the dissimilarity value for each painting with the painting's average abstraction level rating, obtained from a separate set of participants.

Dissimilarity per region. To understand where in the brain abstract paintings elicited more variable activity than representational paintings, we computed regional cross-subject dissimilarity in BOLD response patterns in selected ROIs. Response patterns consisted of activation in each voxel in the respective ROI averaged over the time points that the stimulus was on the screen. We then computed the dissimilarity (1-Pearson's r) between each subject's pattern of activity for each painting, resulting in a subject x subject RDM for each painting, and take the median of this matrix as our cross-subject dissimilarity measure for each painting. Finally, we compared the distribution of dissimilarities for abstract paintings with the distribution of dissimilarities for representational paintings, using an independent-samples t-test. We then modeled the effect of abstraction level on dissimilarity using linear regression, controlling for mean activation in each region. We performed this analysis for each ROI tested and corrected for multiple comparisons using the False Discovery Rate method (63).

Mean activation in the region. We computed average activation in each region for each painting as the average activation across all voxels in the region, averaged across participants. We then used this per-painting value as a regressor in our models of regional dissimilarity, to control for differences in mean activation of the region.

ROI selection. We selected regions from the Harvard Oxford Atlas involved in processes that comprise art viewing. To test the hypothesis that differences in activity across participants might be due to differences in low-level visual information content, we selected regions in early visual cortex–the occipital pole, occipital fusiform gyrus, ICC, and the SCC. We also hypothesized that participants might be imputing objects, faces, or scenes onto the abstract paintings. This should result in dissimilarity in areas involved in face recognition, object recognition, and scene construction. These regions included the temporal occipital fusiform cortex, the posterior temporal fusiform cortex, the anterior temporal fusiform cortex, the temporal occipital inferior temporal gyrus, posterior inferior temporal gyrus, anterior inferior temporal gyrus, the posterior parahippocampal cortex, and the anterior parahippocampal cortex (*SI Appendix*, Fig. S4). To test our third hypothesis, that people are using higher-level cognitive processes to impart meaning onto abstract art, we looked at two core nodes of the DMN—the PC, shown to vary with varying interpretations of a narrative (15), and the FMC, which overlaps to the vmPFC, a region involved in subjective value (64) as well as aesthetic response (7).

Model of regional cross-subject dissimilarity. We ran a multivariate linear regression to model the relationship between abstraction level of painting and cross-subject dissimilarity in patterns of activation in a region of interest, while controlling for BOLD activation in that region. *(Cross-subject Dissimilarity ~ Abstraction Rating of Painting + Average BOLD activation)*. *P*-values were obtained by likelihood ratio tests of the full model with the effect of abstraction level against the model without the effect of abstraction level.

Data, Materials, and Software Availability. Some study data have been deposited in OSF (65). All other study data are included in the article and/or *SI Appendix*.

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Supporting Information for

The Beholder's Share: Bridging Art and Neuroscience to Study Individual Differences in Subjective Experience

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Supplementary Text

Effect of abstraction on dissimilarity when controlling for mean activation

We ran a multivariate linear regression to model the relationship between abstraction level of painting and cross-subject dissimilarity in patterns of activation in a region of interest, while controlling for BOLD activation in that region. In the Occipital Pole, we do not find a significant difference between the full model and the null model ($F(158,1)=.202$, $p=.65$). In the Precuneus, we find a significant difference between full model and the null model (($F(158,1)=19$, $p<.001$), such that abstraction rating significantly predicts dissimilarity ($b=.015$, $sd=.004$, $p<.001$). In the FMC, we find a significant difference between full model and the null model ($F(158,1)=6.12$, $p<.05$), such that abstraction rating significantly predicts dissimilarity ($b=.005$, $sd=.002$, $p<.01$). Figure S5 shows correlations between abstraction level of painting and cross-subject dissimilarity, the semi-partial correlation of abstraction rating and cross-subject dissimilarity, and the correlation between average BOLD response and cross-subject dissimilarity.

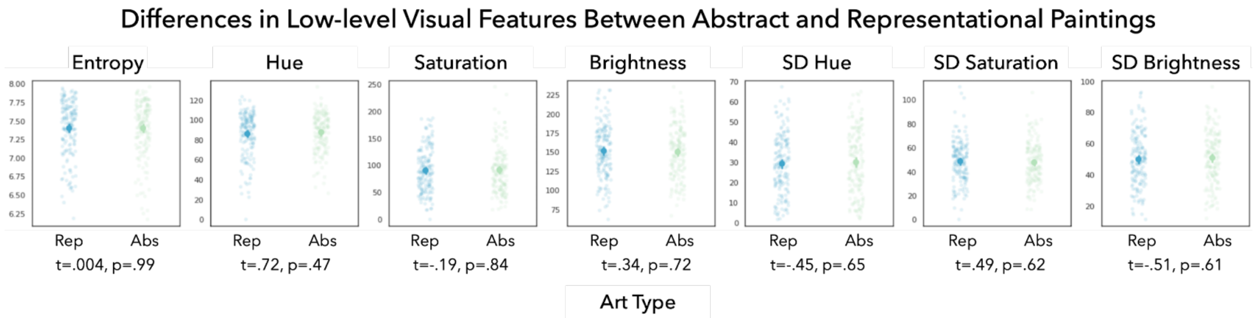

Fig S1. Low-level features do not differ between abstract and figurative paintings. RGB images were transformed into HSV values, using python's skimage toolbox. Seven features were computed using functions from the python skimage toolbox. This included entropy, and the means and standard deviations of brightness, saturation, and hue. We see no differences between low level visual features in abstract and figurative images.

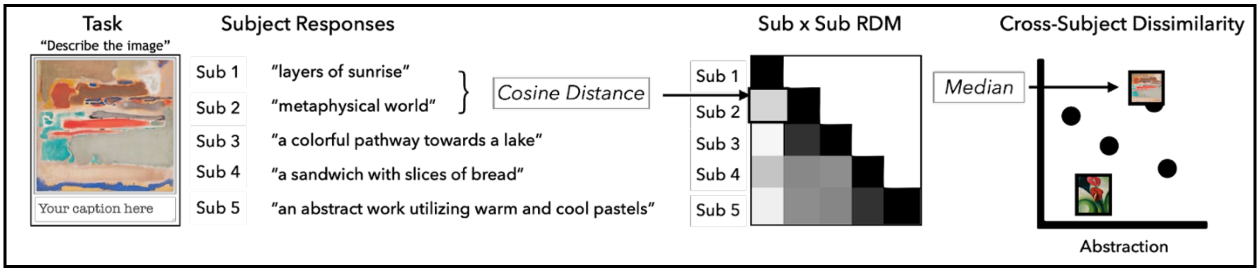

Fig. S2. Measuring individual differences in semantic meaning of captions. Subjects were asked to describe each painting in 280 characters or less. Each subject's caption was then transformed into a feature vector using the Google Sentence Encoder (31). To measure semantic dissimilarity between each subject's response, we computed the cosine distance between each subject's feature vector, resulting in a subject x subject RDM for each painting. The median of this RDM became that painting's cross-subject dissimilarity value. We then looked at the relationship between the cross-subject dissimilarity value and the abstraction rating of the painting.

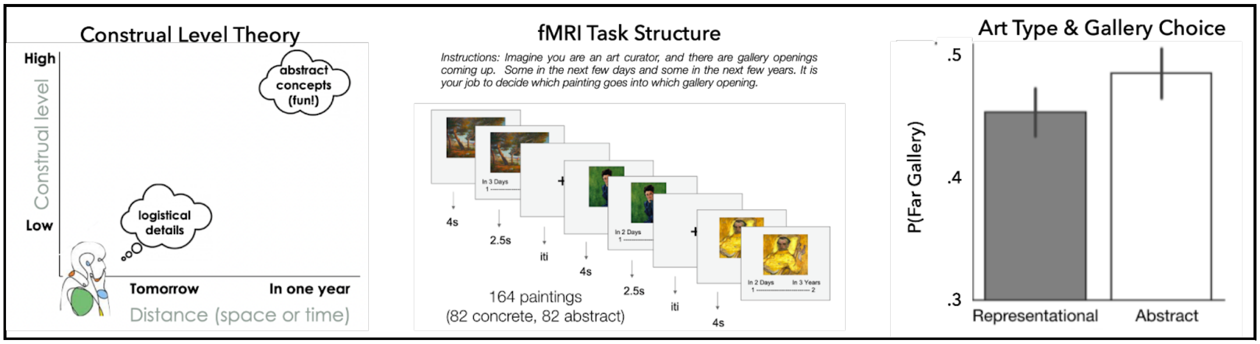

Fig. S3. fMRI Task design and behavioral results. A. Construal level theory. To measure differences in cognitive states elicited by abstract and representational art, we used Construal Level Theory to design our task. Construal Level Theory has shown a relationship between abstraction and future thought, such that objects or events occurring farther in the future are mentally represented more abstractly, and conversely, more abstract objects and events are thought of as more distant (Trope, 2008). **B. fMRI Task Structure**. In an fMRI scanner, subjects saw abstract and representational paintings and were asked to sort each into a gallery opening in the next few days or a gallery opening in the next few years. Each subject completed 164 trials equally divided between four runs (42 trials per run). Each trial lasted a total of 6.5 seconds and consisted of a viewing phase (4 s) and a choice phase (2.5 s). In the modeling below, we considered the full 6.5 second period when measuring neural responses. Each trial was separated by a jittered inter-trial-interval (ITI) drawn from an exponential distribution with a mean of 3. If the value generated was below 1 or above 12, it was redrawn. In the viewing phase, a painting appeared on the screen alone for 4 seconds. Following that, the choice phase began, and answer choices appeared below the painting for 2.5 seconds, during which the subjects were able to make their choice. **C. Behavioral (construal level) results.** Abstract art elicits more temporal distance than representational art, as it is more likely than representational art to be placed in a far gallery.

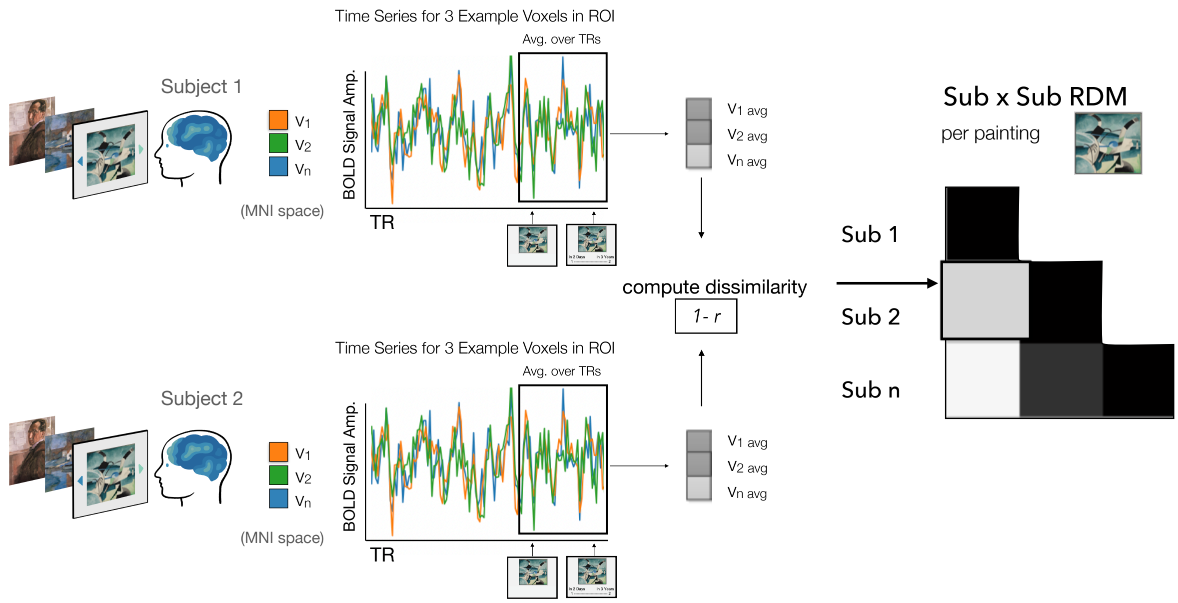

Fig. S4. BOLD Signal Extraction for Regional Dissimilarity Analysis. For each subject, we extracted the BOLD time series using Nilearn's transform function. This function regresses out confounds obtained from fMRI prep, and z-scores the signal across each run. We shifted our stimulus labels by 4.5 seconds to account for hemodynamic lag. The BOLD response to a specific painting was the average BOLD response across all timepoints that the specific painting was on the screen.

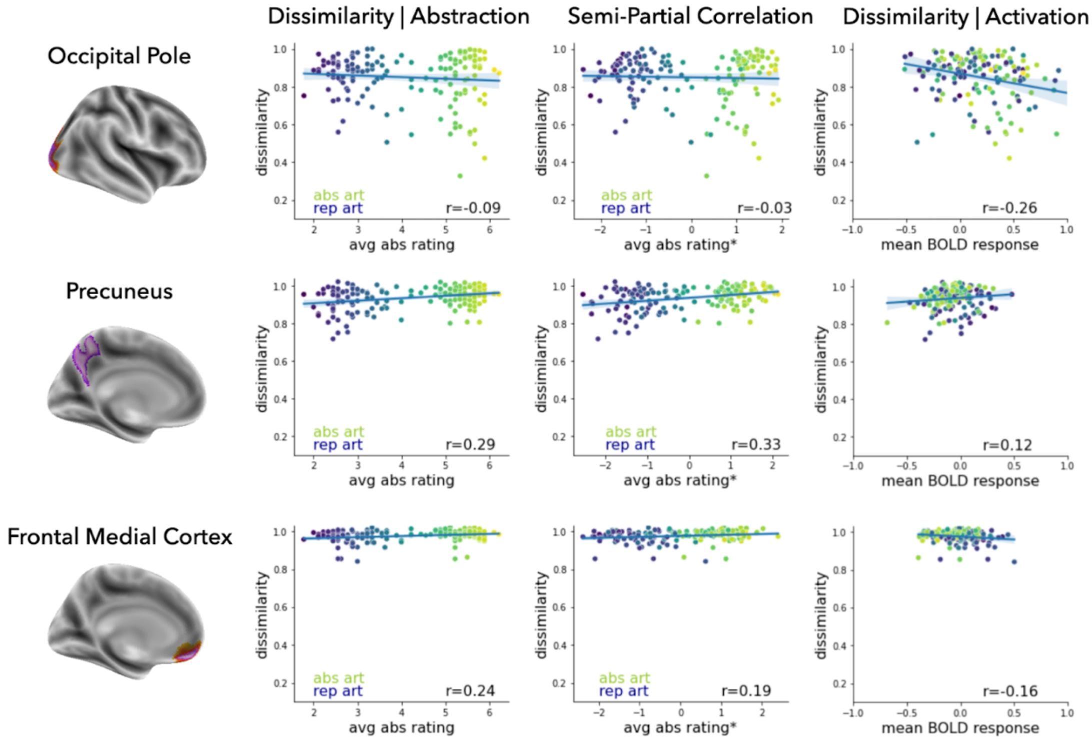

Fig. S5. Examination of the relationship between abstraction rating of painting, mean BOLD activation, and cross-subject dissimilarity. Rows are results for different brain regions. (Left column) **Relationship between Abstraction and Dissimilarity**. The left column shows the overall correlation between abstraction level of painting and dissimilarity. We see a positive correlation in the Precuneus and Frontal Medial Cortex, and a non-significant negative correlation in the Occipital Pole. (Middle Column) **Semi Partial Correlation of Abstraction on Dissimilarity**. To understand how much of the correlation between abstraction rating and dissimilarity was affected by magnitude of BOLD activation, we computed the semi-partial correlation, partialling out magnitude of activation from average abstraction rating (avg. abs rating*). We see that the effect of abstraction on dissimilarity in the Precuneus and Frontal Medial Cortex holds even while controlling for mean activation. (Right column) **Correlation between Activation and Dissimilarity.** The right column shows the correlation between mean BOLD response and Dissimilarity. Mean BOLD response was computed as an average BOLD response in all voxels in a region for all subjects for a particular painting. We find negative correlations between response and dissimilarity in the Occipital Pole and Frontal Medial Cortex, and a positive correlation in the Precuneus. This suggests that the dissimilarity in the Precuneus and Frontal Medial Cortex is not solely a product of less activation.

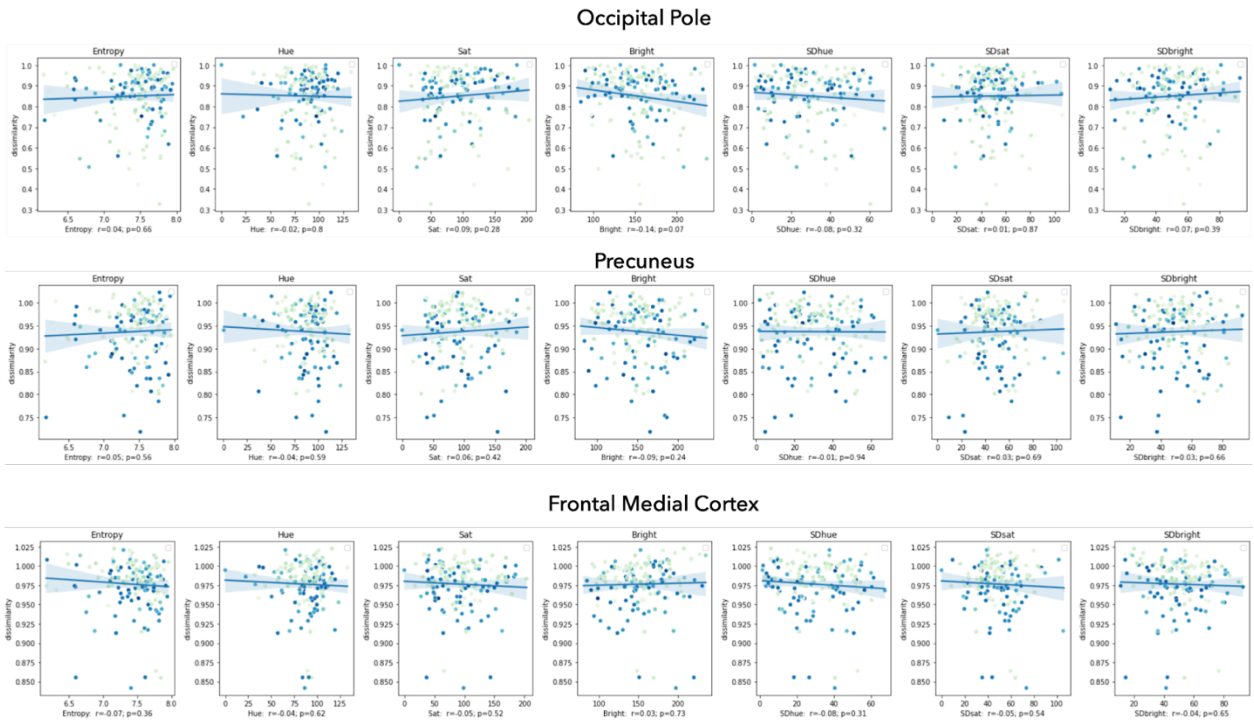

Fig. S6. Correlations between visual features of a painting and its cross-subject dissimilarity. Figure shows this relationship in the Occipital Pole, Precuneus, and Frontal Medial Cortex. Each point represents a painting, colored by abstraction rating (lighter colors more abstract). Cross-subject dissimilarity is not significantly correlated with any low-level features of the art.

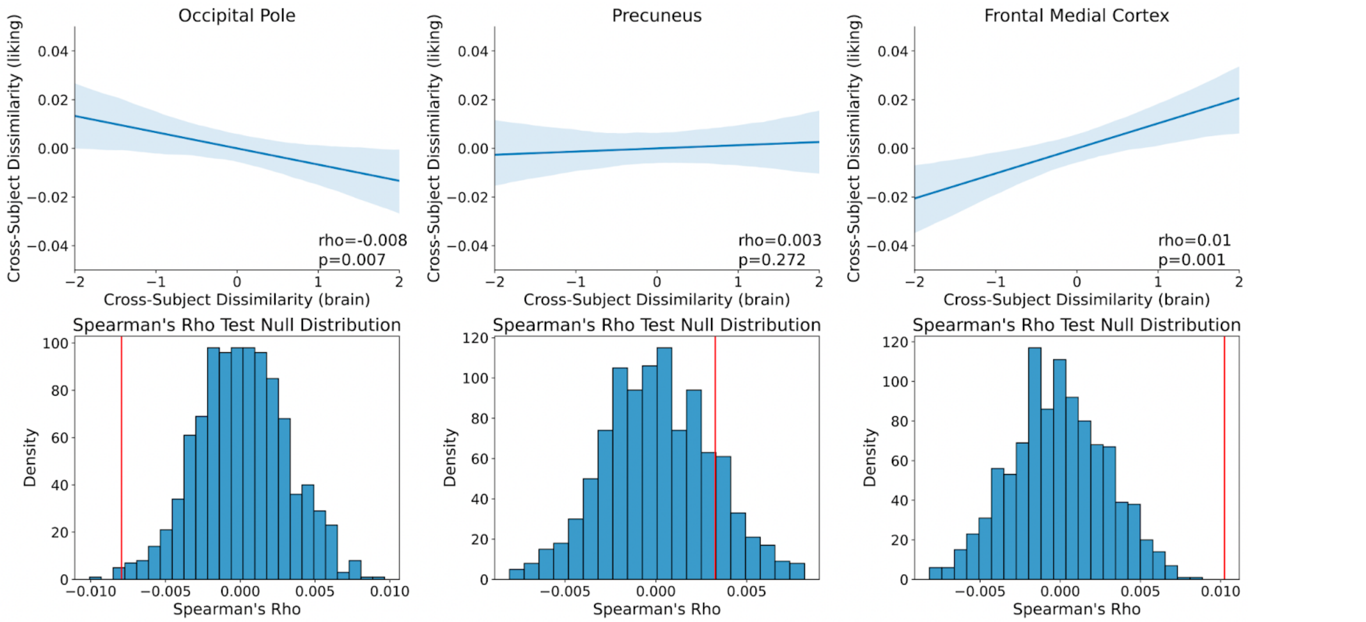

Fig. S7. Correlations between Cross-subject Dissimilarity in Brain Activity and Cross-subject Dissimilarity in Liking of a painting. Top row: Correlations between cross-subject dissimilarity in the brain (x-axis) and cross-subject dissimilarity in liking of a painting (y-axis) for specified regions of interest. Correlations were computed by computing spearman's rho between the vectorized bottom triangle of the subject by subject cross-subject dissimilarity matrix and the vectorized bottom triangle of the subject by subject liking matrix for each painting. **Bottom row:** correlation compared to a null distribution of correlations, obtained by shuffling the brain-dissimilarity values (1,000 permutations). Each permutation randomly shuffled the brain-dissimilarity values and correlated this new vector with the liking values. We find that in the Frontal Medial Cortex, distance between subject's patterns of brain activity significantly correlates with distance between their liking of the painting. We do not find this in the Precuneus or the Occipital Pole.

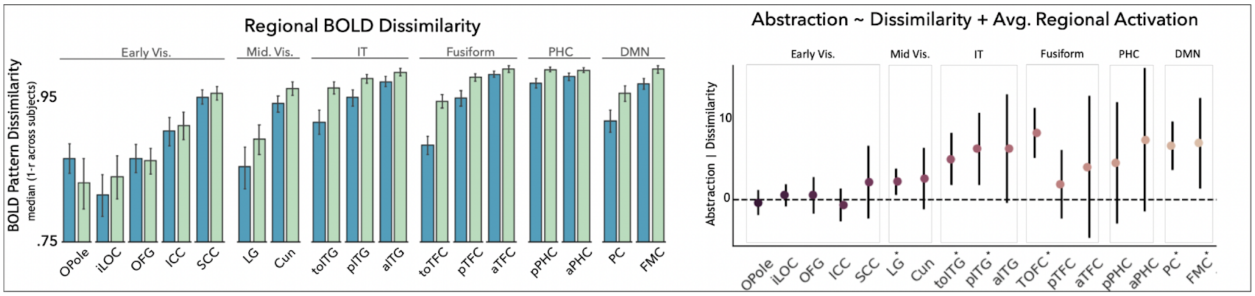

Fig. S8. Cross-subject dissimilarity in all regions tested. A. Comparisons of cross-subject dissimilarity in neural representations between abstract and figurative paintings. Error bars represent standard error. B. **Model predicting abstraction given dissimilarity.** Dissimilarity coefficients from linear regression model predicting abstraction of the painting by painting's dissimilarity, adjusting for average activation in the region. * indicates regions with significant (q<0.05) relationship between abstraction level and cross-subject dissimilarity, corrected for multiple comparisons of all regions tested (17 total) using FDR correction.

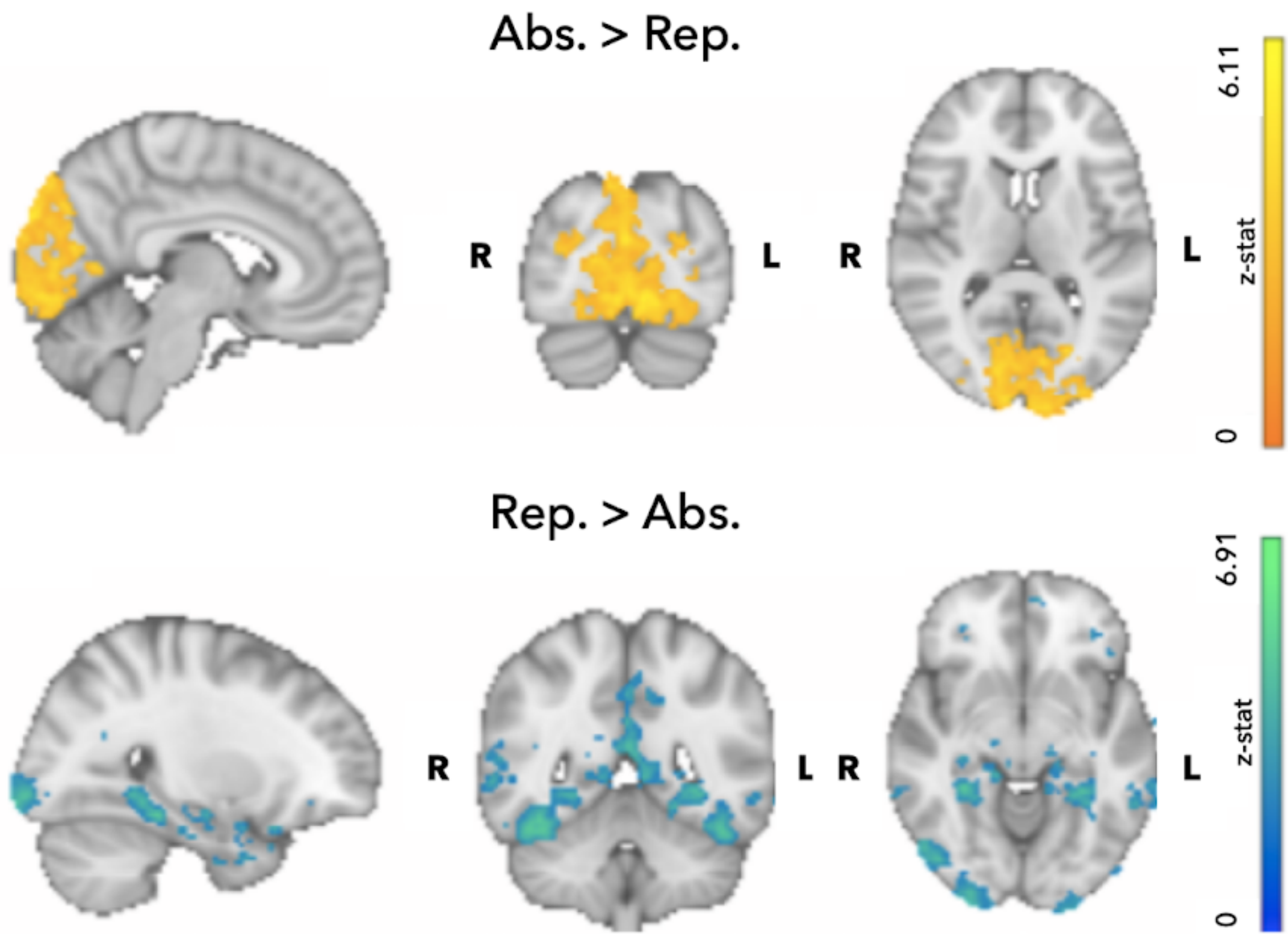

Fig. S9. Whole Brian Analysis for Contrast of Abstract and Representational art. Sagittal (left) and coronal (center) and axial (right) view of activation superimposed over a template brain. Results for the contrast Representational > Abstract revealed more activation in the hippocampus and ventral visual stream. Results for the contrast Abstract > Representational revealed more activation in the primary visual cortex and dorsal visual stream. The map was cluster corrected for familywise error rate at a whole-brain level with an uncorrected cluster-forming threshold of $z = 2.3$ and corrected extent of $p<0.05$.

	Cross-subject Dissimilarity				
	Occipital Pole	Precuneus	FMC	Occ. pole * Precuneus	Occ. pole * FMC
Abstraction Rating	-0.003	0.015^{***}	0.005^{*}		
	(-0.019 , 0.012)	(0.008 , 0.022)	(0.001 , 0.009)		
BOLD Activation	-0.099^{**}	0.068^{*}	-0.013		
	(-0.161 , -0.037)	(0.016 , 0.120)	(-0.045 , 0.019)		
Abstraction Rating * Region [Precuneus]				0.260^{*}	
				(0.059 , 0.460)	
Abstraction Rating * Region [Occ. pole]					-0.064
					(-0.249 , 0.120)
Observations	161	161	161	322	322
R^2	0.067	0.119	0.062	0.176	0.353
Adjusted R^2	0.055	0.108	0.050	0.168	0.345
Residual Std. Error	0.125 (df=158)	0.057 (df=158)	0.031 (df=158)	0.914 (df=318)	0.811 (df=317)
F Statistic	5.647^{**} (df=2; 158)	10.695^{***} (df=2; 158)	5.220^{**} (df=2; 158)	22.583^{***} (df=3; 318)	43.217^{***} (df=4; 317)
Note:					$^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table S1.

Regression table for model run predicting cross-subject dissimilarity in activation for different regions from abstract level of painting, adjusting for average BOLD activation in the region.

Anatomic Region	Hemi	Voxels	MNI coordinates x	y	z	Z-MAX	P
Abstract > Representational							
Lingual Gyrus	L	8394	-8	-80	-10	6.92	.0000
Lateral Occipital Cortex, superior	L	280	-20	-68	58	4.35	.0000
Supramarginal Gyrus, anterior	R	120	54	-26	50	4.74	.0055
Representational > Abstract							
Temporal Occipital Fusiform Cortex	R	16292	42	-44	-24	7.67	.0000
Middle Frontal Gyrus	R	1031	52	28	24	5.4	.0000
Cerebellum	R	924	-16	-88	-30	4.61	.0000
Superior Frontal Gyrus	R	598	2	54	26	4.15	.0000
Middle Frontal Gyrus	L	584	-38	20	60	4.09	.0000
Middle Temporal Gyrus, anterior	L	490	-66	-6	-16	5.34	.0000
Frontal Orbital Cortex	L	416	-38	36	-16	4.78	.0000
Brain-Stem	L	373	-10	-48	-44	4.59	.0000
Middle Temporal Gyrus, anterior	R	349	62	-4	-22	4.32	.0000
Frontal Medial Cortex	*	295	0	50	-16	4.99	.0000
Middle Temporal Gyrus, posterior	L	183	-64	-42	-14	4.34	.0001
Frontal Pole	R	145	38	36	-14	4.04	.0012
Superior Frontal Gyrus	R	114	2	28	54	3.39	.0081
Frontal Pole	R	103	24	36	52	3.88	.0167

Table S2. BOLD Activation Clusters for Each Contrast.