Characterising the spatiotemporal profiles of neural object representations using implicit and explicit similarity judgement tasks

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Abstract

Relating behavioural and brain data is essential for understanding how the brain identifies and distinguishes individual objects. Prior work has shown that human brain activity associated with perceived similarity is well explained by explicit behavioural similarity judgements. However the nature of such judgements cannot fully explain representational geometries observed in the visual cortex. Here, we use a combination of behavioural tasks in an attempt to identify behaviourally-relevant brain representations across the visual ventral stream. We derived behavioural representations from three tasks: an explicit multi-arrangements task, a high-level semantic labelling task, and an implicit same-different task. We investigate the spatiotemporal neural profiles of these behavioural representations by comparing behavioural representations with fMRI and EEG recordings using representational similarity analysis (RSA). All three task representations correlated highly with neural activity in anterior regions of the ventral stream at time points associated with late stage visual processing. Additionally, the same-different task exhibited high correlations propagating throughout the ventral stream in more posterior regions, as well as at earlier time points. These results highlight the importance of using implicit similarity judgements to complement the neural information explained by higher-level, conscious similarity judgements.

Keywords: Similarity Judgments; RSA; Spatiotemporal Fusion; Visual Representations; Behavioral Experiments

Introduction

Linking neural and behavioural activity is pivotal in understanding and replicating the neural mechanisms responsible for visual stimulus recognition. Behavioural experiments involving perceived similarity judgments have become increasingly used in visual experiments, providing behavioural representations which strongly associate with visual system activity (Hebart et al., 2020; Waraich & Victor, 2022). Representational similarity analysis (RSA) is an effective method to identify commonalities between representations of neural and behavioural activity. RSA utilises representational dissimilarity matrices (RDM), symmetrical matrices describing the level of dissimilarity between each pair of stimuli in a set (Kriegeskorte, Mur, & Bandettini, 2008). To compare RDMs between brain and behaviour, behavioural similarity judgements must be measured between all pairs of stimuli. When dealing with a large number of stimulus conditions, the psychophysical experiments used to measure similarity judgments must be efficient. The multiple arrangements (MA) task (Kriegeskorte & Mur, 2012) has proven to be highly efficient when compared with tasks of a similar nature (Giordano et al., 2011), collecting multiple pairwise similarity judgements in a single trial. This has proven invaluable in successfully relating different explicit behavioural information about stimuli to representational geometries of brain activity patterns. (Bankson et al., 2018; Charest et al., 2014; Cichy et al., 2019; Mur et al., 2013), explaining ventral stream dynamics across both space and time (Bankson et al., 2018; Cichy et al., 2019). Such experiments rely on highly explicit similarity judgements, in which conscious (and presumably high-level) decisions from participants determine the outcome of the similarity space. Such decisions presumably do not reflect representational geometries across the whole visual cortex (King et al., 2019). Here, we investigate how implicit and explicit similarity judgments capture complementary components of brain-behaviour relations. To fully capture these processes, we collected data from three tasks of varying levels of processing; an (implicit) same-different task, an (explicit) MA task, and a semantic-level captioning task. We compare how information measured from these tasks associates with the spatiotemporal unfolding of object representations encoded in the ventral stream, by relating it to both EEG (temporal) and fMRI (spatial) activity.

Methods

All stimulus conditions were identical to Charest et al. (2014). In the MA task, subjects were instructed to organise stimuli in a circular “arena” according to their similarity. The euclidean distance between pairs of stimuli on the 2D plane were taken as a dissimilarity metric. Next, implicit similarity judgements were recorded using a same-different task. Two stimuli were concurrently presented to the subject very briefly (17ms), followed by a dynamic mask (200ms). Subjects were then asked whether the two images displayed were different or identical. The task responses and reaction times were then input to a drift-diffusion model (Vandekerckhove et al., 2011), and the drift rate used as an index of representational distance. The third task required participants to describe a given stimulus in a sentence. The sentences were then encoded in embedding space using MPNet (Song et al., 2020), and the level of similarity between sentences computed as the cosine distance between their respective vectors. All three tasks yielded one RDM per participant, characterising the pairwise dissimilarities across all stimulus pairs.

The fMRI data (3T, n=20) used in this study was previously described in Charest et al. (2014). GLMdenoise (Charest et al., 2018; Kay et al., 2013) was used to provide voxel-wise beta estimates, and a univariate noise normalisation (Misaki et al., 2010). was used before computing the RDMs using correlation distances (1 - Pearson r). Comparison with behavioural RDMs was done in spherical searchlights (6mm diameter) that covered the whole brain.

The EEG data (128 channel, n=20) was collected separately from the behavioural and fMRI data. The stimuli described in Charest et al. 2014 were presented in a one-back task, each stimulus being displayed for 500 ms. Linear discriminant analysis (LDA) was performed on the EEG data from which cross-validated (k-fold) decoding accuracy between stimulus pairs was used as a distance metric, producing an RDM for each time point between -500ms and 1500ms from image onset.

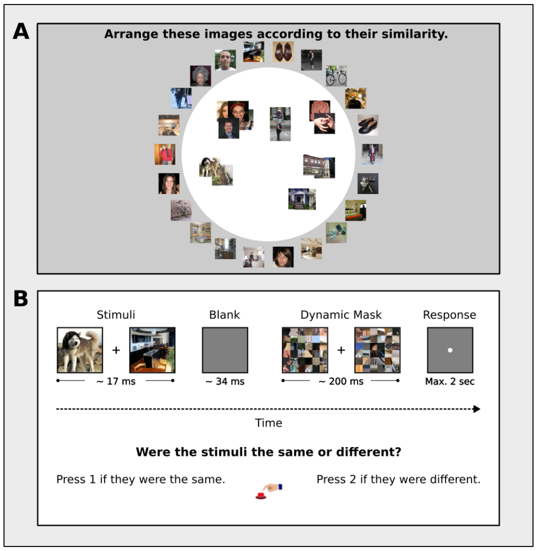

Figure 1: Behavioral similarity judgment procedures. A) Multiple Arrangements B) Same-Different Task.

Results

We revealed the spatio-temporal unfolding of task representations in the brain by computing the spearman r correlations between task RDMs and i) searchlight-defined RDMs of fMRI activity across the brain, as well as ii) EEG derived RDMs for each point in time (figure 2; all significant correlation shown are FDR-corrected at a significance level of p ¡ 0.05). To identify regions and time profiles associated with high level object features, we used a high level semantic labelling task which showed high levels of correlation in the anterior regions of the ventral pathway, with a peak correlation (r=0.41) in human inferior temporal cortex (hIT), whereas much lower levels of correlation were observed in earlier ventral areas. Temporal correlations peaked at 164 ms after stimulus onset (peak r=0.17), and gradually declined after. The results observed for the semantic labelling task are consistent with previous studies linking abstract feature processing to late ventral stream (Bankson et al., 2018; Doerig et al., 2022; Kriegeskorte, Mur, Ruff, et al., 2008; Popham et al., 2021). Correlations from the explicit MA task closely mirrored those observed in the semantic labelling task both spatially and temporally, with a peak spatial correlation (r=0.41) also in IT, and a peak temporal correlation again at 164 ms from stimulus onset (peak r=0.19). Finally, our implicit same-different task also revealed high levels of correlation in hIT (r=0.48). However, the same-different task also revealed similarities distributed across earlier stages of the ventral stream (figure 2). Temporally, the same-different task exhibited a similar pattern and level of temporal correlation to the explicit tasks from 164 ms onwards, with a sharp increase followed by a gradual decline. However, the same-different task also exhibited higher levels of correlation at times closer to stimulus onset, with a larger peak correlation (r=0.29) occurring at 156 ms.

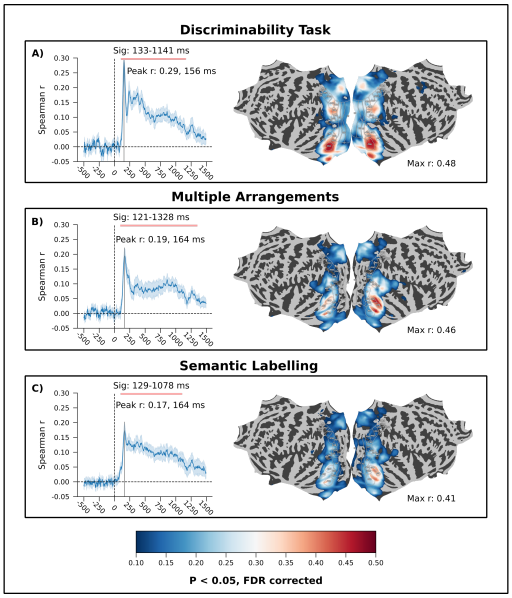

Figure 2: Temporal (left) and Spatial (right) Spearman r values (blue) and areas of significance (red) for A) Discriminability Task B) Multiple Arrangements C) Semantic Labelling.

Discussion

This study compared how behavioural experiments designed to capture explicit, implicit and high-level semantic similarity judgments explain the spatio-temporal unfolding of object representations in the visual ventral stream. Our results showed that an implicit task, in which conscious decisions about similarity are absent, is a strong behavioural predictor of the neural representational geometry of the visual cortex in both space and time. Compared with explicit similarity judgements, our implicit task was able to explain representational geometries along the visual ventral stream in more posterior as well as in high-level anterior regions. While implicit judgments have been used in the past (Hebart et al., 2020; Magri & Konkle, 2019), the same-different task is not constrained by the need to combine similarity judgments across many participants, allowing single-subject analyses. Indeed, this task has been used previously to investigate idiosyncratic brain and behavioural relationships (Charest et al., 2014), something to which spatio-temporal characterisation could be extended. Altogether, our results highlight how combining behavioural experiments that capture complementary features underlying similarity judgements can provide a more comprehensive spatiotemporal map of neural object representations than either could alone, and provide novel insights about behaviourally-relevant brain representational similarities at different stages of information processing along the visual ventral stream.

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References

Bankson, B. B., Hebart, M. N., Groen, I. I. A., & Baker, C. I. (2018). The temporal evolution of conceptual object representations revealed through models of behavior, semantics and deep neural networks. *Neuroimage*, *178*, 172–182.

Charest, I., Kievit, R. A., Schmitz, T. W., Deca, D., & Kriegeskorte, N. (2014). Unique semantic space in the brain of each beholder predicts perceived similarity. *Proc. Natl. Acad. Sci. U. S. A.*, *111*(40), 14565–14570.

Charest, I., Kriegeskorte, N., & Kay, K. N. (2018). GLMdenoise improves multivariate pattern analysis of fMRI data. *Neuroimage*, *183*, 606–616.

Cichy, R. M., Kriegeskorte, N., Jozwik, K. M., van den Bosch, J. J. F., & Charest, I. (2019). The spatiotemporal neural dynamics underlying perceived similarity for real-world objects. *Neuroimage*, *194*, 12–24.

Doerig, A., Kietzmann, T. C., Allen, E., Wu, Y., Naselaris, T., Kay, K., & Charest, I. (2022). Semantic scene descriptions as an objective of human vision.

Giordano, B. L., Guastavino, C., Murphy, E., Ogg, M., Smith, B. K., & McAdams, S. (2011). Comparison of methods for collecting and modeling dissimilarity data: Applications to complex sound stimuli. *Multivariate Behav. Res.*, *46*(5), 779–811.

Hebart, M. N., Zheng, C. Y., Pereira, F., & Baker, C. I. (2020). Revealing the multidimensional mental representations of natural objects underlying human similarity judgements. *Nat Hum Behav*, *4*(11), 1173–1185.

Kay, K. N., Rokem, A., Winawer, J., Dougherty, R. F., & Wandell, B. A. (2013). GLMdenoise: A fast, automated technique for denoising task-based fMRI data. *Front. Neurosci.*, *7*, 247.

King, M. L., Groen, I. I. A., Steel, A., Kravitz, D. J., & Baker, C. I. (2019). Similarity judgments and cortical visual responses reflect different properties of object and scene categories in naturalistic images. *Neuroimage*, *197*, 368–382.

Kriegeskorte, N., & Mur, M. (2012). Inverse MDS: Inferring dissimilarity structure from multiple item arrangements. *Front. Psychol.*, *3*, 245.

Kriegeskorte, N., Mur, M., & Bandettini, P. (2008). Representational similarity analysis - connecting the branches of systems neuroscience. *Front. Syst. Neurosci.*, *2*, 4.

Kriegeskorte, N., Mur, M., Ruff, D. A., Kiani, R., Bodurka, J., Esteky, H., Tanaka, K., & Bandettini, P. A. (2008). Matching categorical object representations in inferior temporal cortex of man and monkey. *Neuron*, *60*(6), 1126–1141.

Magri, C., & Konkle, T. (2019). Comparing facets of behavioral object representation: Implicit perceptual similarity matches brains and models. *2019 Conference on Cognitive Computational Neuroscience*.

Misaki, M., Kim, Y., Bandettini, P. A., & Kriegeskorte, N. (2010). Comparison of multivariate classifiers and response normalizations for pattern-information fMRI. *Neuroimage*, *53*(1), 103–118.

Mur, M., Meys, M., Bodurka, J., Goebel, R., Bandettini, P. A., & Kriegeskorte, N. (2013). Human Object-Similarity judgments reflect and transcend the Primate-IT object representation. *Front. Psychol.*, *4*, 128.

Popham, S. F., Huth, A. G., Bilenko, N. Y., Deniz, F., Gao, J. S., Nunez-Elizalde, A. O., & Gallant, J. L. (2021). Visual and linguistic semantic representations are aligned at the border of human visual cortex. *Nat. Neurosci.*, *24*(11), 1628–1636.

Song, K., Tan, X., Qin, T., Lu, J., & Liu, T.-Y. (2020). Mpnet: Masked and permuted pre-training for language understanding. *Adv. Neural Inf. Process. Syst.*, *33*, 16857–16867.

Vandekerckhove, J., Tuerlinckx, F., & Lee, M. D. (2011). Hierarchical diffusion models for two-choice response times. *Psychol. Methods*, *16*(1), 44–62.

Waraich, S. A., & Victor, J. D. (2022). A psychophysics paradigm for the collection and analysis of similarity judgments. *J. Vis. Exp.*, (181).