NeuroImage 157 (2017) 586–597

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

Neural representation of geometry and surface properties in object and scene perception

Matthew X. Lowe[a,b,*], Jason Rajsic[b], Jason P. Gallivan[c,d,e], Susanne Ferber[b,f], Jonathan S. Cant[a]

[a] Department of Psychology (Scarborough), University of Toronto, Toronto, ON, Canada M1C 1A4
[b] Department of Psychology (St. George), University of Toronto, Toronto, ON, Canada M5S 3G3
[c] Centre for Neuroscience Studies, Queen's University, Kingston, ON, Canada K7L 3N6
[d] Department of Psychology, Queen's University, Kingston, ON, Canada K7L 3N6
[e] Department of Biomedical and Molecular Sciences, Queen's University, Kingston, ON, Canada K7L 3N6
[f] Rotman Research Institute, Baycrest, Toronto, ON, Canada, M6A 2E1

A R T I C L E I N F O

Keywords:
Structure
Layout
Texture
Visual features
Ventral visual
Context
fMRI

A B S T R A C T

Multiple cortical regions are crucial for perceiving the visual world, yet the processes shaping representations in these regions are unclear. To address this issue, we must elucidate how perceptual features shape representations of the environment. Here, we explore how the weighting of different visual features affects neural representations of objects and scenes, focusing on the scene-selective parahippocampal place area (PPA), but additionally including the retrosplenial complex (RSC), occipital place area (OPA), lateral occipital (LO) area, fusiform face area (FFA) and occipital face area (OFA). Across three experiments, we examined functional magnetic resonance imaging (fMRI) activity while human observers viewed scenes and objects that varied in geometry (shape/layout) and surface properties (texture/material). Interestingly, we found equal sensitivity in the PPA for these properties within a scene, revealing that spatial-selectivity alone does not drive activation within this cortical region. We also observed sensitivity to object texture in PPA, but not to the same degree as scene texture, and representations in PPA varied when objects were placed within scenes. We conclude that PPA may process surface properties in a domain-specific manner, and that the processing of scene texture and geometry is equally-weighted in PPA and may be mediated by similar underlying neuronal mechanisms.

Introduction

In only the briefest of moments, the human visual system is able to draw on a broad array of cues to efficiently identify and navigate complex environments. A fundamental question of visual perception has been how the brain represents scene information to perform this feat. Since its initial description, the parahippocampal place area (PPA) (Epstein and Kanwisher, 1998) has become a critical region for understanding the neural mechanisms underlying this ability, yet diverse claims to its function have produced ongoing debate. Emerging with the initial description of PPA, the influential spatial layout hypothesis posits this region represents the geometric structure of a scene as defined by its background elements. Evidence has since produced support for this hypothesis through the encoding of spatial features within a scene, such as structural geometry or layout (Epstein et al., 2003), spatial boundary (Park et al., 2011), and spatial depth (Kravitz et al., 2011). Conversely, a growing body of work suggests PPA plays a broader role in scene recognition, extending beyond the confines of the spatial layout hypothesis to include the processing of high-level conceptual scene categories (Walther et al., 2009, 2011; Dilks et al., 2011), non-spatial contextual associations of objects (Bar et al., 2008; Aminoff et al., 2007) and events (Diana, 2016), and the surface texture and material properties of isolated objects (Peuskens et al., 2004; Cant and Goodale, 2007, 2011). Evidence further suggests this region connects goal-states and context to construct a flexible neural representation of the environment by integrating multiple visual features diagnostic of scene identity (Lowe et al., 2016). Nevertheless, disentangling and directly comparing the unique contributions of individual visual elements to scene representation has been a central challenge, and previous research has yet to elucidate the relative importance of individual visual features in shaping underlying neural responses, thus leaving these questions unanswered.

Akin to structural features, surface properties are ubiquitous within a scene, and inform our general perception and recognition of the world around us. For instance, Steeves et al. (2004) have shown that a patient with profound visual form agnosia (impairments in processing

* Corresponding author at: Department of Psychology, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON, Canada M1C 1A4.
E-mail address: matthew.lowe@utoronto.ca (M.X. Lowe).

http://dx.doi.org/10.1016/j.neuroimage.2017.06.043
Received 29 December 2016; Accepted 19 June 2017
Available online 21 June 2017
1053-8119/

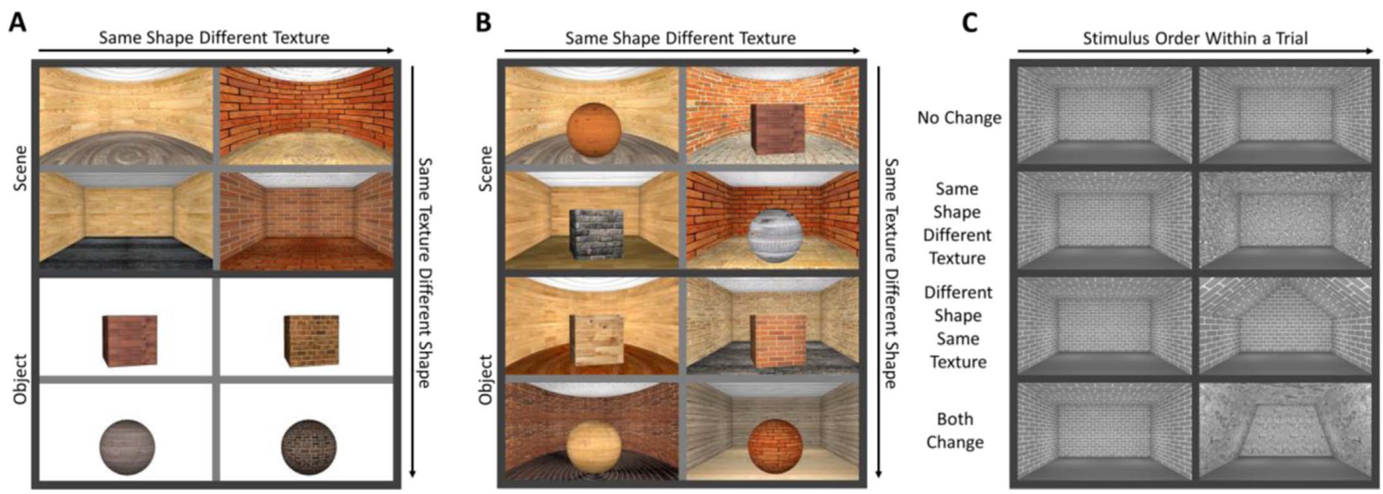

Fig. 1. Experimental Stimuli. (A) Examples of stimuli used in Experiment 1. Scenes and objects are defined by their shape (circular vs. square) and texture (wood vs. brick). Observers attended to the shape or texture of the object or scene, either of which could change while the other was held constant. (B) Examples of stimuli used in Experiment 2. The stimuli and procedure were identical to Experiment 1, with the exception that objects were placed within scenes. (C) Examples of the stimuli used in Experiment 3. Scenes could vary across 10 different shapes, and 10 different textures. In Experiment 3, observers attended only to overall changes across images, and did not attend directly to any one particular feature. For additional examples of the stimuli used in Experiment 3, see Supplementary materials Fig. S1.

structure) was able to use visual texture and colour information for accurate scene recognition, suggesting these visual features play an important role in the formation of scene identity. In object perception, surface characteristics such as texture may facilitate visual search by defining edges (Biederman and Ju, 1988). Moreover, texture is instrumental in providing visual cues which aid in identification and action planning necessary for interacting with objects (Buckingham et al., 2009; Gallivan et al., 2014), and may form a contextual bridge linking an object to its surrounding environment (Lowe et al., 2015). Research has further highlighted the importance of surface properties in the perception of natural scenes, where this feature may be particularly important for the formation of scene identity (Lowe et al., 2016).

In light of the importance of both geometry and surface properties in object and scene perception, the present study aims to directly explore the relative contributions of these features across scene- and object-selective visual cortex in order to ascertain the importance of both geometry and surface properties in shaping representations of our visual world. To accomplish this, we use a novel set of images specifically designed to explore the relative weighting (i.e., levels of univariate activation) of geometry and surface properties in object and scene perception, and then compare neural representations of these features across objects and scenes. We first test the hypothesis that PPA will show equal weighting (i.e., equivalent levels of activation) to the processing of the geometry and surface properties of a scene, but greater sensitivity to the surface properties of an object over its shape (Cant and Goodale, 2007, 2011), when scenes and objects are presented in isolation (Experiment 1). Building on previous behavioral research (Lowe et al., 2015), we next explore object-scene interactions and test the hypothesis that interactions between an object and its background context will modulate the neural relationship of shared visual features (Experiment 2). In this experiment, we combine object and scene images from the previous experiment to form a new set of scenes. Across the first two experiments, we use multivoxel pattern analyses (MVPA) to examine if the processing of scene geometry and surface properties in PPA are mediated by shared or distinct neuronal mechanisms, and also predict that the processing of these visual features in PPA is domain specific to scenes, and thus PPA would show greater activation when processing the surface properties of scenes compared with objects.

Finally, we use the fMR-adaptation approach to obtain a sensitive measure of the relative weighting of geometry and surface properties solely within scene perception in PPA (Experiment 3). Here, we predict equivalent releases from adaptation for variations in scene geometry or surface properties and an interaction (i.e., non-additivity) between the processing of these features, which would imply that their representations are not independent. In addition to examining the PPA, in all experiments we explore how geometry and surface properties contribute to neural representations in regions sensitive to processing scenes (RSC, OPA), objects (LO), and faces (FFA, OFA).

Materials and methods

Observers

Thirty-six paid observers with normal or corrected-to-normal visual acuity were recruited from the University of Toronto community, consisting of ten paid observers (6 male; mean age 26.2 ± 4.92) in Experiment 1, twelve paid observers (6 male; mean age 25.83 years ± 3.61) in Experiment 2, and fourteen paid observers (6 male; mean age 24.21 ± 3.26) in Experiment 3. All Observers gave informed consent in accordance with the University of Toronto Ethics Review Board. One observer in Experiment 3 was removed prior to analyses due to excessive head motion (i.e., rotation and or translation in excess of 3 mm or 3°, respectively) which could not be motion-corrected within acceptable limits.

Stimuli and procedure

E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA; Experiment 1; Experiment 2) and Matlab (MathWorks, Natick, MA; Experiment 3) were used to control stimulus presentation and collect behavioral responses. Images for all three experiments were rear-projected onto a screen in the MRI scanner (subtending 17.1° × 12.8 of visual angle), and observers viewed stimuli through a mirror mounted to the head coil directly above the eyes. In Experiment 1, stimuli were 512 unique full-colour 3-dimensional indoor scenes and objects rendered using Blender 2.0 software (Stichting Blender Foundation, Amsterdam; Fig. 1**A**) and created by varying a counterbalanced combination of scene-shape (circular; square), scene-texture (wood; brick), object-shape (circular; square), and object-texture (wood; brick). Textures were heterogeneous within a category (i.e., wood and brick), such that each category contained multiple exemplars of the same type of texture, as would be experienced in real-world environ-