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Exploring the role of space-defining objects in constructing and maintaining imagined scenes

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ABSTRACT

It has recently been observed that certain objects, when viewed or imagined in isolation, evoke a strong sense of three-dimensional local space surrounding them (space-defining (SD) objects), while others do not (space-ambiguous (SA) objects), and this is associated with engagement of the parahippocampal cortex (PHC). But activation of the PHC is classically associated with scene stimuli. The comparable neural response within PHC to both full scenes and single SD objects, led us to hypothesise that SD objects might play a more critical role in the construction and maintenance of scene representations than SA objects. To test this we used scene construction and deconstruction paradigms, where participants gradually built and maintained scenes using SD, SA and background (wall, floors) items. By examining the order in which each item was added (and later removed) to (and from) a scene, we could estimate the significance of each item type. In two different experiments, participants chose SD over SA objects and background items as the first and most critical item in their constructed scenes and, more generally, selected SD objects earlier than SA objects across the scene construction process. When deconstructing scenes, participants retained significantly more SD objects than SA objects, and the last remaining object across all scenes was highly likely to be an SD object. SD objects therefore enjoy a privileged role in scene construction and maintenance, and appear to be an essential building block of scenes.

1. Introduction

For many years, vision, cognitive, and neuro-scientists have studied the nature, perception and memory of scenes (Bar, 2004; Biederman, 1972; Biederman, Mezzanotte, & Rabinowitz, 1982; Bisiach & Luzzatti, 1978; Enns & Rensink, 1990; Epstein & Kanwisher, 1998; Henderson & Hollingworth, 1999; Intraub & Richardson, 1989; Mandler & Parker, 1976; Oliva & Schyns, 1997; Potter & Faulconer, 1975). The identification of a region in posterior parahippocampal cortex (PHC), which appears to be preferentially responsive to topographic information (Aguirre, Detre, Alsop, & D'Esposito, 1996) and scene stimuli (Epstein, Harris, Stanley, & Kanwisher, 1999; Epstein & Kanwisher, 1998), has focused much attention on the neural mechanisms underpinning scene processing. However, what specific scene attributes are represented within the PHC has been widely debated (Ranganath & Ritchey, 2012), and numerous hypotheses, which focus on different aspects of scenes, have been proposed. These include their spatial layout or global structure (Epstein, 2008; Epstein et al., 1999; Park, Brady, Greene, & Oliva, 2011; Walther, Chai, Caddigan, Beck, & Fei-Fei, 2011), contextual (Bar, 2004; Bar, Aminoff, & Schacter, 2008) or categorical (Naselaris, Prenger, Kay, Oliver, & Gallant, 2009; Walther, Caddigan, Fei-Fei, & Beck, 2009) information, scene novelty (Howard, Kumaran, Olafsdottir, & Spiers, 2011), or navigational relevance (Janzen & van Turennout, 2004). Moreover, the distinctive network of brain regions (which includes the PHC), activated when participants actively imagine complex, coherent scenes (Hassabis, Kumaran, & Maguire, 2007; Summerfield, Hassabis, & Maguire, 2010), recall episodic memories, plan for the future or engage in spatial navigation (Buckner & Carroll, 2007; Hassabis & Maguire, 2007; Schacter, Addis, & Buckner, 2008; Spreng, Mar, & Kim, 2009), suggests that understanding scene processing in regions such as PHC may be key to elucidating a range of cognitive functions (Hassabis & Maguire, 2007, 2009).

In a recent study Mullally and Maguire (2011) offered an alternative account of PHC function (see Kravitz, Peng, & Baker, 2011; and Doeller & Kaplan, 2011, for related discussions), proposing that the PHC is selectively engaged by representations that depict local three-dimensional space. Scenes, by their very nature, invariably encompass this. However, Mullally and Maguire (2011) reported that certain types of objects, when imagined or viewed in isolation, evoked a strong sense of three-dimensional local space surrounding them. Such objects were identified as 'space-defining' (SD) objects, whereas objects that did not evoke this impression were referred to as 'space-ambiguous' (SA) objects. Critically when the neural responses to these two object categories were compared,

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a robust signal in the posterior parahippocampal cortex was observed associated specifically with the SD objects (Fig. 1). Importantly, this response was not explained simply by object size alone (Konkle & Oliva, 2012) or contextual associations (Bar et al., 2008). The location of this PHC activation mirrored that typically observed when scene stimuli are compared to single objects (Epstein & Kanwisher, 1998; Epstein et al., 1999; O'Craven & Kanwisher, 2000). Thus, Mullally and Maguire (2011) argued that the three-dimensional space inherently present in scenes but also evident at a more local level in relation to SD objects, may represent the key attribute processed by the PHC (see also Zeidman, Mullally, Schwarzkopf, & Maguire, 2012).

The question remains however, as to whether SD objects are behaviourally relevant to scenes in a way that SA objects are not. In order to examine the relationship between SD objects and scenes, we adapted a technique previously devised by Summerfield et al. (2010), where participants were required to construct indoor scenes in the mind's eye, item-by-item. The items presented to participants were typical household objects and background elements (such as walls and floors). The incremental presentation of items ensured that the scene construction process was 'slowed-down' into distinct steps which could then be individually interrogated. Using this paradigm, we had participants construct scenes in the imagination, using a combination of SD and SA objects (Experiment 1), plus background items (Experiment 2). The order in which the items were presented was not predetermined. Instead, on each trial participants were presented with a written description of the items simultaneously, and constructed their scenes, item-by-item, while noting the order in which the items were added to their imagined constructions (Fig. 2). The participants' overall goal was to achieve the impression of a real-world scene as early in the scene construction process as possible. Thus, by examining the order in which participants chose to add items into their constructions, the category of items considered to be the most influential in the construction of scenes was revealed. We hypothesised that SD objects would be selected earlier in the scene construction process than either SA objects (Experiments 1 and 2) or background items (Experiment 2). In addition, we asked participants to subsequently deconstruct their imagined scenes. This enabled us to examine which object category was most critical in the maintenance of scenes. Again, we predicted that as participants sought to preserve their scene constructs, SD objects would be retained more often than either SA objects or background items.

Despite the extensive research that has been performed on scenes over the last five decades this is, to our knowledge, the first study exploring how mentally generated scene representations are specifically constructed and maintained, and the SD/SA categorisation enabled us to elucidate the significance of three-dimensional local space in this process.

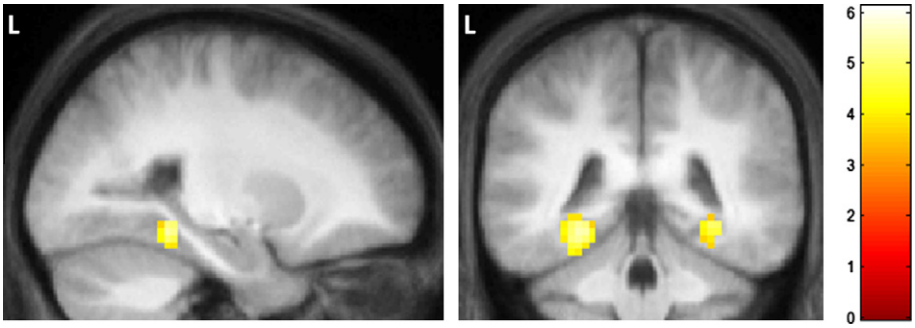

Fig. 1. Brain areas engaged by imagining SD relative to SA objects. Activations at the level of the peak left PHC voxel are shown on sagittal (left panel) and coronal (right panel) images on the averaged structural MRI scan of the 21 subjects from the Mullally and Maguire (2011) study. The colour bar indicates the *z*-scores associated with each voxel. L = left side of the brain.

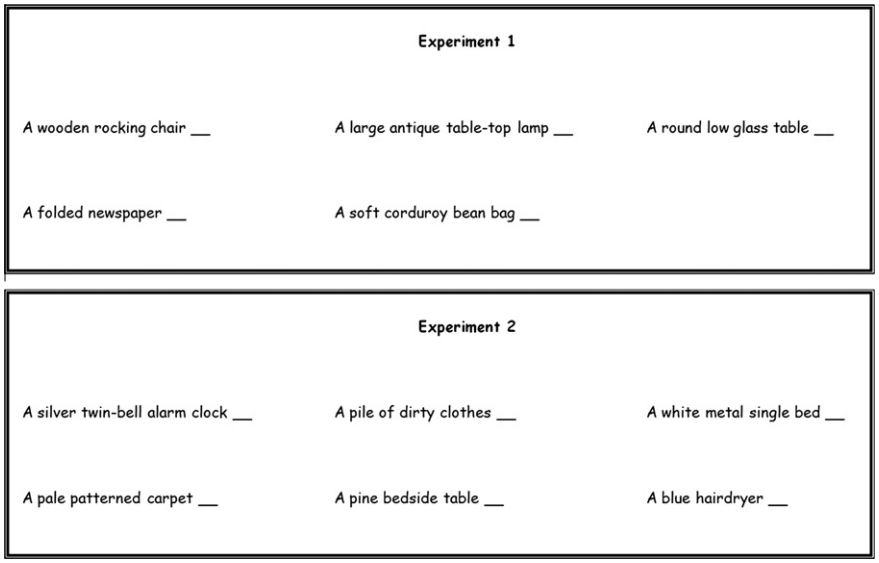

Fig. 2. Example stimuli. Example stimulus for Experiment 1 comprised of SD and SA items, and for Experiment 2 comprised of SD, SA and background elements.