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**Research Articles: Behavioral/Cognitive**

**Retrosplenial cortex indexes stability beyond the spatial domain**

**Stephen D. Auger and Eleanor A. Maguire**

*Wellcome Centre for Human Neuroimaging, Institute of Neurology, University College London, London, WC1N 3BG, UK*

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Corresponding author: Eleanor A. Maguire, Wellcome Centre for Human Neuroimaging, Institute of Neurology, University College London, 12 Queen Square, London, WC1N 3BG, UK; [e.maguire@ucl.ac.uk](mailto:e.maguire@ucl.ac.uk)

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10 Wellcome Centre for Human Neuroimaging, Institute of Neurology,  
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18 Corresponding author: Eleanor A. Maguire, Wellcome Centre for Human  
19 Neuroimaging, Institute of Neurology, University College London, 12 Queen  
20 Square, London, WC1N 3BG, UK; [e.maguire@ucl.ac.uk](mailto:e.maguire@ucl.ac.uk)  
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37

38    **Abstract**

39    Retrosplenial cortex (RSC) is highly responsive to landmarks in the environment  
40    which remain fixed in a permanent location, and this has been linked with its known  
41    involvement in scene and spatial processing. However, it is unclear if RSC  
42    representations of permanence are a purely spatial phenomenon or whether they  
43    extend into behavioural and conceptual domains. To test this, during functional  
44    MRI (fMRI) scanning we had people (males and females) read three different types  
45    of sentence which described either something permanent or transient. The first two  
46    sentence types were imageable, with a focus either on a spatial landmark or on an  
47    action. The third type of sentence involved non-imageable abstract concepts. We  
48    found that, in addition to being more active for sentences describing landmarks with  
49    a permanent location in space, RSC was also significantly engaged by sentences  
50    describing stable and consistent behaviours or actions, as long as they were rooted  
51    within a concrete imageable setting. RSC was not responsive to abstract concepts,  
52    even those that embodied the notion of stability. Similarly, it was not engaged by  
53    imageable sentences with transient contents. In contrast, parahippocampal cortex  
54    was more engaged by imageable sentences describing landmarks, while the  
55    hippocampus was active for all imageable sentences. In addition, for imageable  
56    sentences describing permanence, there was bidirectional functional coupling  
57    between RSC and these medial temporal lobe structures. It appears, therefore, that  
58    RSC-mediated permanence representations could be helpful for more than spatially  
59    mapping environments, and may also provide information about the reliability of  
60    events occurring within them.

61

62

63    **Significance statement**

64    The retrosplenial cortex (RSC) is known to process information about landmarks in  
65    the environment that have a fixed, permanent location. Here we tested whether this  
66    permanence response was apparent beyond the spatial domain, which could have  
67    implications for understanding the role of the RSC more widely across cognition.  
68    We found that the RSC was engaged not only by permanent landmarks, but also by  
69    stable and consistent actions. It was not responsive to transient landmarks or  
70    actions, or to abstract concepts, even those that embodied the notion of stability. We  
71    conclude that the RSC might do more than help to map spatial environments, by  
72    possibly also providing information about the reliability of events occurring within  
73    them.

74

75    **Key words**

76    Retrosplenial; landmarks; actions; concepts; imageable; scenes; fMRI

77

## 78 **Introduction**

79 The retrosplenial cortex (RSC) plays a well-established role in processing scenes  
 80 and spatial information (Iaria et al., 2007; Epstein, 2008; Vann et al., 2009; Galati et  
 81 al., 2010; Auger et al., 2012, 2015; Marchette et al., 2014; Vedder et al., 2016;  
 82 Shine et al., 2016; Alexander and Nitz, 2017; Jacob et al., 2017; Mao et al., 2017).  
 83 Indeed it is commonly included among “scene-selective” brain regions (Dilks et al.,  
 84 2011; Golomb et al., 2011; Nasr et al., 2011, 2013). It has been suggest that RSC  
 85 may help localise and orient a scene within wider environmental representations  
 86 (Park and Chun, 2009; Epstein and Vass, 2014; Hindley et al., 2014). Alternatively,  
 87 it might make spatial comparisons (Nasr et al., 2013) or translate between  
 88 allocentric and egocentric representations of space (Byrne et al., 2007; Vann et al.,  
 89 2009).

90  
 91 It has also been proposed that RSC could in fact be concerned with the coding of  
 92 landmarks which do not move and are permanently located in space, and this may  
 93 explain its engagement in scene and spatial studies (Auger et al., 2012, 2015, 2017;  
 94 Auger and Maguire, 2013). To date, however, permanence has only been  
 95 considered in terms of spatial processing. This leaves important questions regarding  
 96 the scope and purpose of these representations untested. Given that other brain  
 97 areas, like the hippocampus, have a clear role in, but also beyond, spatial cognition,  
 98 in the current study we investigated whether the RSC too might play a more wide-  
 99 ranging role in indexing permanent, non-landmark, features and concepts.

100

101 Responses analogous to scene-selectivity have been demonstrated when people read  
 102 sentences describing concrete, rather than abstract, situations (Wallentin et al.,

2005; Wang et al., 2010). Here, we built upon these findings and created three different types of sentence to investigate the scope of RSC permanence representations. The first sentence type was designed to be directly analogous to previous studies which used visual images of landmarks (Auger et al., 2012), and comprised imageable sentences that mentioned either a permanent or transient landmark. The second sentence type, also imageable, focussed upon permanent or transient actions, rather than landmarks. Finally, there were sentences describing non-imageable abstract concepts, but which nevertheless varied in terms of their permanence. Participants read these sentences during fMRI scanning. They were unaware of the experimental manipulations and performed an incidental vigilance task.

This sentence-reading paradigm provided scope to examine several issues. First, we could test whether the previous findings of RSC engagement for permanent landmarks were replicated in this sentence reading task. Next, and of particular interest, we were able to investigate whether RSC was responsive to stimuli where the focus was not on spatial features like landmarks but instead on permanent actions. We could also assess whether the RSC's reach extended even further into the realm of abstract concepts. Two other brain regions often described as being scene-selective are parahippocampal cortex (PHC) and the transverse occipital sulcus (TOS; Nasr et al., 2011; Bettencourt and Xu, 2013). Here we could test whether they were engaged by the imageable sentences in general or instead by particular features described in the sentences. Similarly, the hippocampus has been linked with visual imagery and the mental construction of scenes, so we were also interested to know how it would respond the imageable and non-imageable

128 sentences (Hassabis and Maguire, 2007, 2009; Maguire and Mullally, 2013;  
129 Zeidman and Maguire, 2016).

130

131 We had a strong hypothesis that RSC would respond to imageable sentences that  
132 described permanent landmarks, in line with the previous literature in the visuo-  
133 spatial domain (Auger et al., 2012, 2015, 2017; Auger and Maguire, 2013). Given  
134 the dearth of studies examining permanence beyond spatial cognition, it was  
135 unclear whether or not RSC would be responsive to sentences describing stable and  
136 consistent actions, and non-imageable abstract concepts. This study would,  
137 therefore provide novel insights into the parameters within which the RSC operates.

138

## 139 **Materials and Methods**

### 140 *Participants*

141 Twenty healthy, right handed participants, with normal or corrected-to-normal  
142 vision and who were highly proficient in reading and speaking English (10 females,  
143 mean age 22.2 years, SD 3.2) took part in the behavioural ratings experiment.

144

145 Thirty two healthy, right handed participants, none of whom had taken part in the  
146 ratings study, participated in the main fMRI experiment (16 females, mean age 21.6  
147 years, SD 3.9). All had normal vision and were highly proficient in reading and  
148 speaking English.

149

150 All participants in both experiments gave written informed consent in line with the  
151 policy of the local research ethics committee.

152

153 *Stimuli*

154 We first created a set of 344 sentences. There were 3 different types of sentence and  
 155 within each sentence type there were descriptions which referred to either  
 156 something permanent or transient, giving a total of 6 sentence categories (Figure 1  
 157 shows the numbered categories and examples of each). The first sentence type  
 158 explicitly referred to a spatial feature or landmark – “landmark” condition – which  
 159 was either permanent or transient, for example, category 1 - permanent: “Everybody  
 160 uses the village post-box”, where the post-box is a landmark that is fixed and does  
 161 not move; category 2 - transient: “People walk past the pile of rubbish”, where the  
 162 rubbish is transient and will not stay fixed in a location. The second type of  
 163 sentence – “action” condition – referred to a permanent or transient action, for  
 164 example, category 3 - permanent: “The chef always creates complex dinners”,  
 165 where the chef reliably performs this action; category 4 - transient: “The drummer  
 166 misses some performances”, where the drummer is not so reliable or stable in terms  
 167 of this action. The third type of sentence – “abstract” condition – described abstract  
 168 concepts which were permanent or transient, for example, category 5 - permanent:  
 169 “Humans are capable of enduring friendships”, which implies a reliable and stable  
 170 concept; category 6 - transient: “The climate is constantly changing”, where the  
 171 climate is not fixed or stable.

172

173 This set of sentences was first characterised in a behavioural ratings experiment,  
 174 and then a closely-matched set of 300 were selected for use in the fMRI study. For  
 175 both the ratings and fMRI experiments, sentences were displayed in black, size 50,  
 176 Calibri font, in the centre of a screen with a grey background.

177



178 ***Behavioural ratings experiment***

179 The goal of the ratings experiment was to ensure the 6 sentence categories used in  
180 the fMRI experiment were matched according to a range of different features. There  
181 were two rounds of questioning in which participants rated different features of the  
182 sentences. In each round, the 344 sentences were presented in a randomised order  
183 one after the other for 4 seconds and each was immediately followed by some  
184 questions.

185

186 The first round of questioning sought to characterise the imageability of the  
187 sentences and vividness of any image they evoked. For each sentence, participants  
188 were first asked: “Does this sentence bring an image of an item or scene into your  
189 mind’s eye?” to which they could reply with one of three options: “*No image*”, an  
190 image of a “*Single item*” or image of a “*Full scene*”. If they indicated that the  
191 sentence did bring an image to mind (either of an item or a scene) they were then  
192 asked whether this image was “*Weak*” or “*Strong*”.

193

194 When designing the sentences, we aimed to ensure that they all referred to ordinary,  
195 everyday items/actions and that the descriptions were clear and unambiguous. We  
196 tested whether this was the case in the second round of questioning. Participants  
197 were again shown the sentences one at a time in a different order. For each one they  
198 first rated: “Is the thing described in the sentence ordinary?” and chose either  
199 “*Ordinary*” or “*Out of the ordinary*”. After giving this response, participants were  
200 then asked “Does anything else, not mentioned in the sentence, come to mind?”;  
201 they indicated either “*Yes*” or “*No*”, and if the former, they were then asked what it  
202 was that came to mind.

203

204 After collecting this set of ratings, we first excluded any sentences which were  
 205 consistently considered unusual (where more than  $5 - 1/4$  – participants rated it  
 206 “*Out of the ordinary*”). Any sentences in categories 1-4 which more than 7 ( $\sim 1/3$ )  
 207 participants said it brought no image to mind were also excluded, as these landmark  
 208 and action sentences were expected to evoke imagery. In contrast, for the abstract  
 209 sentences (categories 5 and 6), where more than 7 participants said it brought an  
 210 image to mind, then those sentences were excluded, because we wanted these  
 211 sentences to be abstract and non-imageable. Finally, we excluded any sentences  
 212 which more than 2 people said brought to mind something else which was not  
 213 mentioned in the sentence. We used these ratings to select an optimised set of 300  
 214 sentences which were closely matched across the 6 categories (50 sentences per  
 215 category) for the fMRI experiment (Figure 2).

216

217 *Statistical analyses:* The matching between the 6 categories was confirmed by a  
 218 series of two-way ANOVAs with two levels for permanence (permanent and  
 219 transient) and three levels of sentence type (landmark, action and abstract). The  
 220 results were as follows: percentage of sentences regarded as ordinary (main effect  
 221 of permanence:  $F_{1,294} = 1.141$ ,  $p = 0.3$ ; main effect of sentence type:  $F_{2,294} = 2.865$ ,  
 222  $p = 0.06$ ; interaction:  $F_{2,294} = 0.406$ ,  $p = 0.7$ ); number of sentences where anything  
 223 else came to mind (main effect of permanence:  $F_{1,294} = 0.191$ ,  $p = 0.7$ ; main effect  
 224 of sentence type:  $F_{2,294} = 0.191$ ,  $p = 0.8$ ; interaction:  $F_{2,294} = 2.479$ ,  $p = 0.09$ );  
 225 percentage of sentences which brought an image into the mind’s eye (main effect of  
 226 permanence:  $F_{1,294} = 0.005$ ,  $p = 0.9$ ; main effect of sentence type:  $F_{2,294} = 1155.068$ ,  
 227  $p < 0.001$ , partial Eta squared effect size = 0.887; interaction:  $F_{2,294} = 0.918$ ,  $p =$

0.4) – note that a significant difference between sentences in categories 1-4 versus categories 5 and 6 was expected as the sentences were specifically designed to have different imageability. This difference was also reflected in an ANOVA demonstrating a greater tendency for the sentences in categories 1-4 to bring a “*Full scene*” to mind than categories 5 and 6 (main effect sentence type:  $F_{1,296} = 246.174$ ,  $p < 0.0001$ , partial Eta squared effect size = 0.454; main effect of permanence:  $F_{1,296} = 0.256$ ,  $p = 0.6$ ; interaction:  $F_{1,296} = 0.008$ ,  $p = 0.9$ ). On occasions we therefore refer to sentences in categories 1-4 as imageable and in categories 5 and 6 as non-imageable.

The sentence categories were further matched for the properties of the words they contained, namely the number and length of words: mean number of words (main effect of permanence:  $F_{1,294} = 0.071$ ,  $p = 0.8$ ; main effect of sentence type:  $F_{2,294} = 0.176$ ,  $p = 0.8$ ; interaction:  $F_{2,294} = 0.045$ ,  $p = 1.0$ ); mean word length (main effect of permanence:  $F_{1,294} = 0.070$ ,  $p = 0.8$ ; main effect of sentence type:  $F_{2,294} = 1.180$ ,  $p = 0.3$ ; interaction:  $F_{2,294} = 0.409$ ,  $p = 0.7$ ).

We also matched the sentences for word frequency to ensure that the sentences did not differ in the amount of rare or uncommon words they contained. For this, we used a frequency list generated from the 100 million word British National Corpus (Kilgarrieff, 1997). Specifically, the 6 categories were carefully matched for the mean word frequency of their low-frequency words (those with a frequency less than 0.025%; main effect of permanence:  $F_{1,294} = 0.576$ ,  $p = 0.4$ ; main effect of sentence type:  $F_{2,294} = 0.081$ ,  $p = 0.9$ ; interaction:  $F_{2,294} = 0.000$ ,  $p = 1.0$ ).

253 This provided us with a set of thoroughly characterised sentences, which were  
 254 rigorously matched.

255

#### 256 *Stimuli and task for the fMRI experiment*

257 For the fMRI experiment, in addition to the optimised set of 300 sentences from the  
 258 ratings study, we included 50 additional nonsensical sentences to serve as the basis  
 259 of an incidental vigilance task that would be performed during scanning, for  
 260 example, “Looking through murky with market planning”. The nonsense sentences  
 261 were specifically designed so that their first few words could potentially form a  
 262 meaningful sentence (e.g. “Looking through murky”) so that it was not immediately  
 263 obvious if a sentence was nonsense. This ensured that participants had to read  
 264 sentences in full to establish their meaning. In this way, we could be confident that  
 265 everyone was reading all the sentences in their entirety. The 50 nonsense sentences  
 266 were also completely matched to sentences in the 6 main categories for the length,  
 267 number and frequency of their words (mean word length:  $F_{6,343} = 0.826$ ,  $p = 0.6$ ;  
 268 mean number of words:  $F_{6,343} = 0.410$ ,  $p = 0.9$ ; mean word frequency:  $F_{6,343} =$   
 269  $0.571$ ,  $p = 0.8$ ).

270

271 While undergoing fMRI scanning, participants were presented with the 350  
 272 sentences and performed a simple vigilance task. They were instructed to read each  
 273 sentence carefully and press a button if the sentence they were reading was  
 274 “complete and utter nonsense”. This ensured that they paid attention to the  
 275 sentences and their meaning, but without drawing attention to any particular  
 276 sentence feature. No mention was made about any of the key differences between  
 277 the sentences and there were no instructions that they should try to picture what was

278 being described. This ensured that participants were completely naïve about the key  
279 manipulations of interest, which was crucial in order to allow an unbiased  
280 assessment of neural responses evoked by the different sentence categories.

281

282 The 350 sentences were presented one at a time for 4 seconds each in a  
283 pseudorandomised order – this was achieved by randomising stimulus order until  
284 there was an even distribution of the 6 categories and nonsense sentences across the  
285 whole scanning period. There was a 2 to 4 second jittered interval separating the  
286 sentences during which a black fixation cross was shown in the centre of a grey  
287 background. Participants pressed a button with their right index finger if they  
288 thought the sentence they were reading was nonsense and were instructed to do  
289 nothing for sentences they thought were sensible. Pressing the button caused the  
290 trial to immediately end and move on to the next inter-trial fixation period. All  
291 nonsense sentences and any extra trials on which subjects pressed the button were  
292 removed from the fMRI analysis. The 350 trials were split into 3 scanning runs of  
293 approximately 13.5 minutes each.

294

295 Immediately after scanning was completed, participants were debriefed. The aim of  
296 this debriefing session was to ascertain whether or not they had become aware of  
297 the key differences between sentences while performing the incidental vigilance  
298 task. Participants were first asked: “Did you notice anything in particular about the  
299 sentences?” If they did not articulate any of the differences, participants were then  
300 asked more specifically: “Did you notice any definite pattern in what the sentences  
301 described or were they just random?” Finally, they were presented with a list of  
302 twelve different possible ways in which the sentences might have varied and were

303 instructed to identify one of the options they thought was correct. Eleven of the  
 304 options were incorrect foils (e.g. “the type of font the sentences were written in”)  
 305 and there was only one correct option (“described either permanent or transient  
 306 things”). Participants then had to indicate how confident they were in their selection  
 307 (*Guessing, Not confident, Fairly confident, Very confident*).

308

### 309 *Scanning parameters and preprocessing*

310 T2\*-weighted echo planar images (EPI) with BOLD contrast were acquired on a 3T  
 311 whole body MRI scanner (Magnetom TIM Trio, Siemens Healthcare, Erlangen,  
 312 Germany). We used a 32-channel head receive coil and the standard RF transmit  
 313 body coil. Scanning parameters were optimised for the hippocampus and  
 314 surrounding tissue whilst still achieving whole brain coverage: 48 oblique axial  
 315 slices angled at  $-45^\circ$  from the axial to coronal plane (as defined in Weiskopf et al.,  
 316 2006), 2.5 mm thickness (with inter-slice distance factor 20%), repetition time TR =  
 317 3.36s (slice TR = 70 ms), echo time TE = 30 ms, echo spacing 500  $\mu$ s, matrix size =  
 318 64 $\times$ 74, 13% oversampling in the PE direction, excitation flip angle =  $90^\circ$ , in-plane  
 319 resolution 3 mm $\times$ 3 mm, field of view FoV = 192 mm $\times$ 192 mm phase encoding  
 320 (PE) in the anterior-posterior direction. For reduction of signal loss in the  
 321 hippocampal region, slices were angulated and a z-shim gradient moment of +0.6  
 322 mT/m\*ms was applied (Weiskopf et al., 2006). The first 6 ‘dummy’ volumes from  
 323 each scanning run were discarded to allow for T1 equilibration effects. Field maps  
 324 were acquired with a standard manufacturer’s double echo gradient echo field map  
 325 sequence (short TE = 10 ms, long TE = 12.46 ms; 64 axial slices with 2 mm  
 326 thickness and 1 mm gap yielding whole brain coverage; in-plane resolution  
 327 3mm $\times$ 3mm). A 3D MDEFT T1-weighted structural scan (Deichmann et al.,

2004) was acquired for each participant with 1 mm isotropic resolution. fMRI data were analysed using SPM8 ([www.fil.ion.ucl.ac.uk/spm](http://www.fil.ion.ucl.ac.uk/spm); RRID:SCR\_007037). Images were bias corrected, realigned and unwarped (using the field maps), normalised to a standard EPI template in MNI space with a resampled voxel size of 3×3×3mm and smoothed using an 8mm FWHM Gaussian kernel.

### *fMRI: first- and second-level statistics*

After preprocessing, we performed a series of whole brain univariate fMRI analyses using a general linear model. Each trial was modelled as the full 4 seconds that a sentence was on display and we applied the default SPM high-pass filter cut-off of 128 seconds with no global normalisation.

Each of the univariate fMRI contrasts described in the sections below were run using the same general linear model, with one regressor of interest for each of the six sentence types. A separate regressor was included for the nonsense sentences and any trial on which the button was pressed (i.e., those that a participant thought were nonsense). This regressor and the individual movement regressors were treated as covariates of no interest. Regressors of interest were convolved with the canonical haemodynamic response function. Subject-specific parameter estimates pertaining to each contrast (betas) were calculated for each voxel. Second level random effects analyses were run on these parameter estimates (collapsing across scanning runs) using one-sample t-tests. We report any fMRI activations that survived a whole brain family-wise error (FWE) corrected threshold of  $p < 0.05$  unless otherwise stated. Given our strong hypotheses regarding engagement of the RSC in relation to permanence, we report any increased activity in this region at a

whole brain uncorrected threshold of  $p < 0.001$  for contrasts pertaining to permanence.

#### *fMRI: the interaction between sentence type and permanence*

In the first instance, we considered fMRI responses in relation to the interaction between whether sentences were imageable (categories 1-4) or not (categories 5 and 6) and their permanence. We then performed a second interaction analysis, this time only considering imageable sentences, to look for responses which were sensitive to permanence and whether sentences described a landmark (categories 1 and 2) or an action (categories 3 and 4).

#### *fMRI: differences between sentence types*

We examined responses related to the type of sentence, independent of whether what was being described was permanent or transient. To do this, we compared imageable sentences (categories 1-4) with non-imageable sentences (categories 5 and 6). Within the imageable categories, we also contrasted fMRI responses to landmark sentences (categories 1 and 2) with action sentences (categories 3 and 4).

#### *fMRI: differences in permanence*

We then examined responses associated with permanence. To do this, we first performed separate analyses of permanent and transient sentences. We contrasted permanent imageable sentences (categories 1 and 3) with permanent non-imageable sentences (category 5), and then permanent landmark sentences (category 1) with permanent action sentences (category 3). We did the same for the transient sentences. Next, we directly compared permanent with transient imageable



378 sentences (categories 1 and 3 versus categories 2 and 4). In addition, we separately  
 379 contrasted permanent and transient landmark (category 1 versus category 2) and  
 380 action (category 3 versus category 4) sentences. For all the permanent versus  
 381 transient sentences contrasts described, we also performed corresponding analyses  
 382 to look for any regions which might be more active for transient sentences.

383

#### 384 *Connectivity analyses*

385 For the regions shown to be engaged by imageable sentences, we then examined  
 386 how they interacted with other brain areas in relation to the permanence of what  
 387 was being described. Each of the activation clusters identified in the univariate  
 388 analyses (at a threshold of  $p < 0.001$  for RSC and  $p < 0.05$  FWE corrected for the  
 389 whole brain) were used as seed regions in generalised psycho-physiological  
 390 interaction (gPPI) analyses (McLaren et al., 2012). Specifically, we looked for any  
 391 brain areas which had increased functional coupling with the seed regions on  
 392 permanent compared to transient trials. The precise contrast used for each seed  
 393 region corresponded to the univariate contrast from which they were derived. The  
 394 gPPI analyses were performed using the “Generalised Form of Context-Dependent  
 395 Psychophysiological Interactions” SPM toolbox (McLaren et al., 2012) and we  
 396 report any significant results at a whole brain uncorrected threshold of  $p < 0.001$  for  
 397 the RSC (given our specific prior hypotheses regarding permanence processing in  
 398 this region) and  $p < 0.05$  FWE corrected for the rest of the brain.

399

400 Any significant interactions between regions identified in the gPPI analyses were  
 401 further examined using Dynamic Causal Modelling (DCM; Friston et al., 2003).  
 402 DCM allows the comparison of different models of task-dependent effective

connectivity between pre-specified brain areas. We specifically investigated the permanence based causal influence between brain regions already shown to have permanence-related interactions with one another (from the gPPI analyses). We used stochastic DCM (Daunizeau et al., 2012) which accounts for endogenous fluctuations in brain activity. This is of particular relevance here as our participants were not directly viewing what was described in the sentences, so much of the network's activity will have been driven by endogenous brain processes (rather than purely external experimental manipulations).

The design matrix used for the DCM analysis contained two main regressors: one for all imageable sentences (categories 1-4) and a second for just permanent imageable sentences (categories 1 and 3). The first was to be used for the models' input (the DCM C matrix) and the second for modulatory connections (B matrix). DCM10 was used for the analysis and we assumed there to be reciprocal endogenous connections between the regions as well as self-connections (A matrix). All plausible models of interaction between the regions were compared. These differed in the connections which were modulated by permanence (B matrix) and the region which received the system's driving input (C matrix) (see Figure 5B for exact model architectures). Each of the models' predicted haemodynamic responses were fitted to the actual fMRI data in each participant and compared using a random effects bayesian model comparison to establish the most likely "winning" model (Stephan et al., 2009).

428 **Results**

429 ***Behavioural***

430 Behavioural responses made by participants while they were performing the  
431 vigilance task inside the scanner indicated that they successfully maintained  
432 attention. The mean error rate (missed or inappropriate ‘nonsense’ responses) was  
433 very low throughout for all participants (mean error rate = 3.1%, SD 2.9).

434

435 After scanning, participants were asked if they noticed any patterns or differences in  
436 what the sentences described. None of the 32 participants made reference to being  
437 aware of any difference in whether sentences described something permanent or  
438 transient. When presented with a list of twelve options for the way in which the  
439 sentences could have varied, seven of the thirty-two participants correctly identified  
440 that the sentences described something either permanent or transient. All of those  
441 seven indicated that they only considered this after seeing it on this list of options in  
442 the debriefing, and even then they were not particularly confident in their choice:  
443 four stated they were “*Not confident*”, three “*Fairly confident*” and none were “*Very*  
444 *confident*”. Thus, during fMRI scanning, no participant seemed to have been  
445 consciously aware of the crucial distinction between permanent and transient  
446 sentences and even when aided, only 3 could pinpoint the distinction with any  
447 confidence. Therefore, any neural responses related to the key features of the  
448 sentences are likely to be from automatic, implicit processing.

449

450

451

452

453 *fMRI: the interaction between sentence type and permanence*

454 From the data generated in the behavioural ratings study, we knew that the  
455 sentences in categories 1-4 were imageable whereas those in categories 5 and 6  
456 were non-imageable.

457

458 We first performed an analysis to examine fMRI responses in relation to the  
459 interaction between a sentence's permanence and whether it was imageable or not.  
460 Significant activations in bilateral RSC (right: 18, -43, 10;  $Z = 5.20$ ; left: -15, -52,  
461 13;  $Z = 4.57$ ) were evident. No other brain region showed increased activity at a  
462 FWE corrected threshold of  $p < 0.05$ . A second interaction analysis considered  
463 responses in relation to whether an imageable sentence described a landmark or an  
464 action, and the permanence of what was being described. No regions were  
465 responsive to this interaction, even at a reduced whole brain uncorrected threshold  
466 of  $p < 0.001$ .

467

468 These results indicate that RSC may be sensitive to the interaction between whether  
469 or not a sentence is imageable and its permanent content, but not whether an  
470 imageable sentence refers to either a landmark or action. To formally assess these  
471 findings further, we then directly interrogated responses in relation to sentence type  
472 and permanence separately.

473

474 *fMRI: differences between sentence types*

475 Comparing responses to imageable sentences (categories 1-4) with non-imageable  
476 sentences (categories 5 and 6) revealed increased activity in parts of the cortex  
477 traditionally labelled as being "scene-selective", the PHC bilaterally (left: -30, -31, -

478 14;  $Z = 10.96$ ; right: 33, -28, -11;  $Z = 6.59$ ) and left RSC (-9, -52, 10;  $Z = 5.93$ ;  
 479 Figure 3A). The bilateral PHC clusters also extended into the hippocampus. The  
 480 TOS did not show increased engagement for imageable sentences. The reverse  
 481 contrast (categories 5 and 6 versus categories 1-4) revealed no significant activation  
 482 at a FWE corrected threshold of  $p < 0.05$ , but at a whole brain uncorrected threshold  
 483 of  $p < 0.001$ , clusters in medial prefrontal (9, 68, 10;  $Z = 5.54$ ), superior posterior  
 484 parietal (-18, -52, 46;  $Z = 5.03$ ) and anterior cingulate (-3, 11, -8;  $Z = 4.78$ ) cortices  
 485 were more active for abstract than imageable sentences.

486

487 Within the imageable sentences, if the focus was on a landmark (categories 1 and  
 488 2), then the left PHC (-27, -34, -20;  $Z = 6.69$ ; Figure 3B) had increased activity  
 489 compared to imageable sentences describing actions (categories 3 and 4). This  
 490 indicates that PHC may in particular process space-related features.

491

492 Thus, RSC, PHC and hippocampus were engaged when people read imageable  
 493 sentences. This response was especially apparent in PHC, and was present when the  
 494 sentence had a particular focus on a spatial landmark rather than an action. So  
 495 whereas PHC processing appears to be concerned with spatial features, RSC and  
 496 hippocampus are perhaps engaged by other factors.

497

#### 498 *fMRI: differences in permanence*

499 Having established strong responses to imageable sentences in traditional scene-  
 500 selective cortex, we probed these representations further, taking into account the  
 501 permanence of what the sentences described. For the contrast that demonstrated  
 502 increased activity within RSC, PHC and hippocampus, imageable versus non-

503 imageable sentences, we now separated out permanent and transient sentences.  
 504 Transient imageable sentences (categories 2 and 4) produced significantly greater  
 505 activity in PHC (left: -30, -31, -11;  $Z = 12.52$ ; right: 36, -34, -11;  $Z = 7.07$ ) and left  
 506 posterior-lateral parietal cortex (-45, -76, 34;  $Z = 10.94$ ) than transient non-  
 507 imageable sentences (category 6). Similar to the responses observed for all  
 508 imageable sentences combined (both permanent and transient together), the clusters  
 509 in PHC extended into parts of the hippocampus. However, *unlike* the combined  
 510 permanent and transient imageable sentences, transient imageable sentences did not  
 511 engage RSC more than transient non-imageable sentences, even at a more liberal  
 512 whole brain uncorrected statistical threshold of  $p < 0.005$ . Therefore, if a sentence  
 513 described something transient, RSC lost responsivity to sentences even those that  
 514 were imageable.

515

516 For sentences describing something permanent, a contrast of imageable sentences  
 517 (categories 1 and 3) compared to non-imageable sentences (category 5) revealed  
 518 increased activity within bilateral PHC/hippocampus (left: -33, -37, -8;  $Z = 10.77$ ;  
 519 right: 33, -37, -5;  $Z = 7.12$ ), bilateral RSC (left: -9, -55, 16;  $Z = 8.95$ ; right: 9, -52,  
 520 19;  $Z = 6.61$ ), as well as bilateral posterior-lateral parietal cortex (left: -42, -76, 34;  
 521  $Z = 9.04$ ; right: 45, -61, 28;  $Z = 7.40$ ) and right inferior-lateral parietal cortex (54, -  
 522 7, 10;  $Z = 8.85$ ).

523

524 Whereas PHC and hippocampus were responsive to all imageable sentences, either  
 525 permanent or transient, RSC was only engaged when the landmark or action  
 526 described in a sentence was permanent. We then contrasted fMRI responses to  
 527 permanent and transient sentences directly. There was significantly greater activity

528 in bilateral RSC (left: -12, -52, 13;  $Z = 3.92$ ; right: 18, -46, 10;  $Z = 3.77$ ), but not  
 529 any other brain region, for permanent compared to transient imageable sentences  
 530 (categories 1 and 3 versus categories 2 and 4; Figure 4A).

531  
 532  
 533 We also directly compared permanent and transient sentences separately for  
 534 landmark and action sentences. Increased activity in RSC, but no other brain region,  
 535 was still evident for permanent compared to transient landmarks (category 1 versus  
 536 category 2: 21, -43, 4;  $Z = 3.46$ ) and permanent compared to transient actions  
 537 (category 3 versus category 4: -9, -52, 16;  $Z = 3.46$ ). For permanent versus transient  
 538 non-imageable abstract sentences (category 5 versus category 6), there was no  
 539 difference in RSC activity, even at the reduced whole brain uncorrected threshold of  
 540  $p < 0.005$ . At a whole brain uncorrected threshold of  $p < 0.001$ , bilateral  
 541 dorsolateral prefrontal cortex (DLPFC), was more active for permanent than  
 542 transient abstract sentences (right: 42, 53, 7;  $Z = 5.37$ ; left: -51, 44, 4;  $Z = 4.95$ ;  
 543 Figure 4B), as well as posterior parts of the occipital lobes (right: 15, -85, 10;  $Z =$   
 544 5.58; left: -9, -88, 4;  $Z = 4.93$ ) and the cerebellum (-36, -58, -47;  $Z = 4.80$ ).

545  
 546 We also compared landmark and action permanent and transient sentences  
 547 separately (categories 1 versus category 3; category 2 versus category 4). Here,  
 548 when the permanence of sentences being compared was the same, PHC was the  
 549 only region more active for landmark than action sentences for both permanent  
 550 (left: -27, -31, -20;  $Z = 4.83$ ; right: 30, -34, -17;  $Z = 4.02$ ) and transient (-30, -34, -  
 551 20;  $Z = 5.63$ ) sentences (at a whole brain uncorrected threshold of  $p < 0.001$ ), with  
 552 no evidence of RSC engagement even at the more liberal uncorrected whole brain  
 553 threshold of  $p < 0.005$ .

554

555 We also performed similar comparisons to all those mentioned above, but looking  
556 instead for brain areas more engaged by transient than permanent sentences. None  
557 of these comparisons revealed any significant activation in any brain region.

558

559 RSC was therefore consistently more engaged by permanent than transient  
560 sentences but only if the sentences described something that was imageable. This  
561 was the case when comparing both permanent and transient landmarks and also  
562 actions. Indeed, RSC lost all sensitivity to imageable sentences if what was being  
563 described was transient. No similar sensitivity to permanence was evident in PHC  
564 or hippocampus; both were more responsive to sentences that were imageable  
565 irrespective of permanence. For non-imageable abstract sentences, albeit at a more  
566 liberal threshold, the DLPFC, but not RSC, was more active if they described  
567 something permanent.

568

#### 569 *Connectivity between brain regions associated with permanence*

570 We next performed a gPPI analysis using regions identified in the whole brain  
571 univariate contrasts as seeds. Specifically, we assessed how the interactions with  
572 other brain regions might differ for areas shown to be responsive to imageable  
573 sentences (bilateral PHC/hippocampus and left RSC) and sentences describing  
574 landmarks (left PHC) depending on permanence.

575

576 The bilateral clusters in PHC (extending into hippocampus) which were more  
577 engaged when people read imageable sentences than non-imageable sentences also  
578 displayed greater functional coupling with RSC if the sentences described



579 something permanent (-12, -52, 7;  $Z = 3.98$ ; Figure 5A). For the part of left PHC  
580 which was more engaged by landmarks than action sentences, if that sentence  
581 described a permanent rather than a transient landmark, then it also had increased  
582 functional coupling with RSC (15, -46, 10;  $Z = 4.01$ ). Neither of the gPPI analyses  
583 using RSC seed regions showed any significant changes in functional coupling for  
584 permanent versus transient sentences. This perhaps reflects a lack of any brain  
585 regions, other than the RSC itself, which were responsive to permanence. We also  
586 performed equivalent whole brain gPPI contrasts to look for greater functional  
587 coupling for transient compared to permanent sentences. No significant interactions  
588 were present for any of the seed regions. The changes in functional coupling were  
589 specific to permanent trials.

590

591 Thus, across separate measures, the parts of the medial temporal lobe (MTL) which  
592 were responsive to imageable sentences and also imageable sentences describing  
593 landmarks, displayed increased functional connectivity with RSC when what was  
594 being described was permanent. When a sentence was permanent, therefore, RSC  
595 was not only more engaged, but also increased its interaction with other MTL  
596 regions.

597

598 Having established the functional coupling between RSC and MTL regions  
599 specifically for imageable sentences describing something permanent, we used  
600 stochastic DCM to assess the nature of this interaction. The specific regions used in  
601 the DCM analysis were the bilateral parts of the MTL (consisting of bilateral PHC,  
602 extending into hippocampus) which were more engaged by imageable than non-  
603 imageable sentences, and the RSC which was more active for permanent than

transient imageable sentences. Four simple, biologically plausible models of the interaction between these two regions were compared. Motivated by the mass-univariate and gPPI analyses, the DCM analysis considered only imageable trials (categories 1-4) and investigated how interactions between RSC and MTL were modulated when an imageable sentence described something permanent (categories 1 and 3). The structures of the 4 models were as follows (Figure 5B): Model 1 had RSC as the input region and RSC then driving responses in MTL for permanent imageable sentences; Model 2 was the same but in the opposite direction, with input coming through MTL and MTL then driving RSC permanence responses; Models 3 and 4, had bidirectional modulatory connections, but with the driving input to the system coming through RSC and PHC respectively. The winning model was Model 3 (Model 3 exceedance probability = 0.71, Model 1, 2 and 4 exceedance probabilities all <0.15) and this accounted for an average of 89.5% (SD 4.3) of the variance in the participants' fMRI data. This indicates that for imageable sentences describing something permanent, RSC and MTL were modulating each other's responses, but the input to this system came through RSC.

## Discussion

The primary aim of this study was to examine whether the RSC response to permanent, fixed landmarks extended to other stable contexts, in this case reliably performed actions and abstract concepts. We found that in addition to being more active for sentences that described landmarks which maintained a permanent location in space, RSC was also significantly engaged by sentences describing permanent behaviours or actions, as long as they were rooted within a concrete imageable setting. RSC was not responsive to abstract concepts, even those that

embodied the notion of stability. Similarly, it was not engaged by imageable sentences with transient contents. It appears, therefore, that RSC-mediated permanence representations could be helpful for more than spatially mapping environments, and might potentially provide information about the reliability of events occurring within them.

On first impressions, the responses in RSC could appear to reflect scene-selectivity (Dilks et al., 2011; Golomb et al., 2011; Nasr et al., 2011, 2013), given that in the behavioural rating study the imageable sentences were typically rated as evoking images of full scenes rather than single objects. This is also consistent with previous demonstrations of RSC processing concrete rather than abstract sentences (Wallentin et al., 2005; Wang et al., 2010). Indeed, there was greater activity in RSC when comparing fMRI responses for all imageable sentences compared to non-imageable abstract sentences. However, this masked a more nuanced reality. For sentences which described something transient, there was no longer any difference between activity elicited by imageable and non-imageable sentences in RSC. The apparent scene-selectivity was in fact only manifest within a permanent context. This suggests that the role of RSC in scene processing may reflect the processing of permanent features (Auger and Maguire, 2013). RSC processing of scenes has previously been proposed to centre around translating between allocentric and egocentric representations of space (Byrne et al., 2007; Vann et al., 2009). However, this cannot account for the difference we observed related to imageable sentences involving permanent actions. Therefore, while RSC might play some role when translating between spatial reference frames, this may not be the only function of this region.

654

655 Instead, the present study provides further evidence that RSC is primarily involved  
656 in processing permanent, reliable features encountered in our surroundings. Our  
657 previous experiments have consistently demonstrated that RSC processes  
658 landmarks which remain fixed in a single, permanent location, in real-life (Auger et  
659 al., 2012; Auger and Maguire, 2013) and virtual reality (Auger et al., 2015, 2017)  
660 environments. Here, RSC was once again more engaged by permanent than  
661 transient items even when they were simply described in a sentence. This sensitivity  
662 to permanent landmarks did not require them to be used for any sort of complex  
663 spatial manipulation, localising or orientating (Nasr et al., 2013; Epstein and Vass,  
664 2014), just a mere reference to them sufficed.

665

666 This experiment also revealed that RSC permanence representations appear to  
667 extend beyond the purely spatial domain. RSC was not only more engaged by  
668 permanent than transient items, but also for sentences describing a permanent,  
669 regular action. The responsiveness to permanence did not, however, extend to more  
670 abstract concepts, so it seems that RSC involvement requires some sort of  
671 grounding within concrete, tangible settings. It remains to be seen just how  
672 extensive RSC representations of permanent elements are within imageable or  
673 scene-type settings. It is possible that they constitute only a minor by-product of a  
674 neural system whose primary function is to identify reliable landmarks for mapping  
675 space. However, if RSC permanence processing is indeed more generalised, this  
676 would have intriguing implications about the nature and scope of the region's  
677 overall contribution to cognition. RSC processing might, for example, help inform  
678 more wide-ranging models, such as predictive coding, concerning the perception of

679 surprising or unpredictable events in order to help optimise representations of  
680 environments and the behaviour happening within them (Friston, 2010).

681

682 The PHC was more active for imageable compared to non-imageable sentences,  
683 which could reflect its scene-selectivity, given the imageable sentences typically  
684 evoked scene imagery. However, here also the story was not so simple. PHC  
685 showed a preference, not for permanence, but for sentences that described spatial  
686 features, in this case landmarks. This resonates with previous work that linked PHC  
687 to the processing of local space around environmental features (Kravitz et al., 2011;  
688 Mullally and Maguire, 2011).

689

690 Interestingly, another brain region which is frequently considered scene-selective is  
691 the TOS, yet here this region was not recruited. This might be due to the stimuli that  
692 we used. Investigations of scene processing in TOS have typically used images of  
693 scenes (Dilks et al., 2011; Golomb et al., 2011; Nasr et al., 2011; Bettencourt and  
694 Xu, 2013), whereas in the current study the only visual inputs were words. TOS  
695 might therefore be involved in lower-level processing of a scene's visual features.  
696 This would also be consistent with its close proximity to posterior visual regions.  
697 Any imagery that might be generated when reading the sentences could only have  
698 been created from purely endogenous representations.

699

700 This constructive process might perhaps account for the engagement of the  
701 hippocampus for imageable more than non-imageable sentences. It has been  
702 proposed that a function of the hippocampus may be to construct representations of  
703 scenes in the imagination, and this may help account for its involvement in

704 autobiographical memory, spatial navigation and imagining the future (Addis et al.,  
705 2007; Hassabis and Maguire, 2007, 2009; Schacter et al., 2012; Maguire and  
706 Mullally, 2013; Zeidman and Maguire, 2016). If hippocampal engagement truly  
707 reflected the construction of scene imagery, then it follows that its responses should  
708 not differ depending upon whether an imageable sentence described something  
709 permanent or transient, or landmarks or actions. This was indeed the case.

710

711 The specific features of imageable sentences to which the different brain regions  
712 were responsive were also linked to the way in which they interacted with one  
713 another. A gPPI analysis showed that the active parts of the MTL (bilateral PHC  
714 extending into hippocampus) interacted with RSC if sentences described something  
715 permanent. A DCM analysis indicated that this interaction was bidirectional, with  
716 the RSC and MTL mutually influencing one another's activity for permanent  
717 imageable sentences, but the input driving the system came through RSC.

718

719 This interaction could reflect a system whereby dependable cues are first identified  
720 within RSC and then integrated into more detailed internal models in the MTL. The  
721 ongoing exchange of information between the brain areas could then reflect  
722 updating and evaluation of existing neural representations, ensuring their long-term  
723 reliability by adapting to what is currently being perceived. In previous  
724 experiments, a similar interaction between the RSC and hippocampus was also  
725 demonstrated in a purely spatial context (Auger et al., 2015). In this instance, RSC  
726 was able to rapidly acquire new permanence representations for previously novel  
727 spatial cues. RSC-hippocampal interactions were then linked to the processing of  
728 detailed knowledge about the specific locations of permanent landmarks within an

729 environment. The present study indicates that the same network could perhaps  
730 contribute to representations of more than just spatial relationships, in this case, also  
731 stable actions.

732

733 The RSC and MTL were not engaged when people read the abstract sentences, even  
734 those that conveyed a sense of permanence. Instead, prefrontal regions responded to  
735 the abstract concepts. The medial prefrontal cortex was more active for abstract  
736 non-imageable compared to imageable sentences, while DLPFC was more active  
737 when people read abstract sentences that described something permanent as  
738 opposed to transient. This was the only permanent-transient contrast that did not  
739 engage RSC, which perhaps reflects the absence of a concrete spatial setting. It is  
740 interesting that the DLPFC, which shares dense reciprocal connectivity with RSC  
741 (Kobayashi and Amaral, 2003), would instead be more active. Of note, this dense  
742 connectivity is not evident in rodents, only in primates (Van Groen and Wyss, 1990,  
743 1992, 2003).

744

745 It is tempting to speculate that this could perhaps reflect a system which has  
746 evolved in primates to carry out more abstract conceptual thinking, but which still  
747 bears some association to lower-level processing of similar themes in the spatial  
748 domain. Thus, whereas RSC processes permanence which is physically embodied  
749 (landmarks, actions), the DLPFC might assume such processing for higher-level  
750 cognition (Powell et al., 2017). However, further work is clearly required to  
751 establish the validity of this conjecture. It may also be possible in the future to  
752 leverage ultra-high-resolution fMRI scanning to examine whether separable sub-  
753 regions within the human RSC respond to permanent landmarks and actions.

754

755 In summary, this study builds upon a previous body of work which indicated that  
 756 RSC specifically processes permanent, stable environmental landmarks. By having  
 757 participants read simple sentences while undergoing fMRI scanning, we were able  
 758 to expand upon these findings and establish the generalisability of RSC engagement  
 759 to include also actions occurring within imageable settings. The responses and  
 760 interactions between brain regions that we observed occurred with participants  
 761 performing a completely incidental task. This suggests that the neural processes  
 762 under consideration are fundamental and automatic. That the RSC might contribute  
 763 to cognition in a more wide-ranging manner than previously thought offers  
 764 intriguing new avenues for future enquiry.

765

766

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887 **Figure 1.** Example sentences from each of the six categories. The numbers are the  
888 category labels referred to in the main text.

889

890 **Figure 2.** Stimulus matching. The sentences used in the fMRI study were very well  
891 matched on a range of features and, as expected, the sentences in categories 1-4  
892 were significantly more imageable than those in categories 5-6. Means  $\pm$  1 SEM.

893

894 **Figure 3.** Brain regions responsive to sentence type. (A) PHC, extending into  
895 hippocampus (left and centre panels) and a small cluster in RSC (right panel)  
896 showed greater activity for imageable sentences, categories 1-4, than non-imageable  
897 sentences, categories 5 and 6. (B) Left PHC showed greater activity for imageable  
898 sentences describing a landmark, categories 1 and 2, than those describing an  
899 action, categories 3 and 4. Activations are shown on views from a single  
900 representative participant's structural MRI brain scan, displayed at a whole brain  
901 FWE corrected threshold of  $p < 0.05$ . The colour bar indicates the Z-scores  
902 associated with each voxel.

903

904 **Figure 4.** Brain regions responsive to permanence. (A) RSC was more engaged by  
905 permanent than transient imageable sentences (categories 1 and 3 versus categories  
906 2 and 4). (B) Dorsolateral prefrontal cortex (DLPFC) and posterior occipital cortex  
907 were more active for permanent than transient non-imageable abstract sentences.  
908 Activations are shown on sagittal and axial views (respectively) of a single  
909 representative participant's structural MRI brain scan, displayed at a whole brain  
910 threshold of  $p < 0.001$  (uncorrected, for display purposes). The colour bar indicates  
911 the Z-scores associated with each voxel.

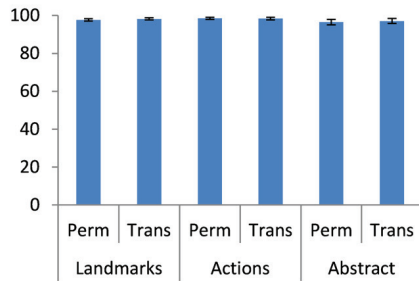
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913 **Figure 5.** Connectivity analyses. (A) Results of the gPPI analysis. RSC (right  
914 panel) had greater functional coupling with medial temporal lobe regions (PHC and  
915 hippocampus; left panel) for permanent imageable sentences. Activations are  
916 displayed on sagittal views of a single representative participant's structural MRI  
917 brain scan. The RSC gPPI activation is displayed at a whole brain uncorrected  
918 threshold of  $p < 0.001$  and the colour bar indicates Z-scores associated with each  
919 voxel. The medial temporal lobe seed region is taken from the whole brain  
920 univariate contrast of imageable sentences, categories 1-4, versus non-imageable

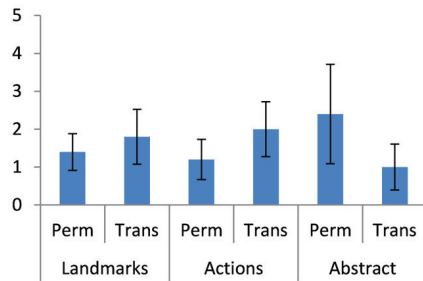
921 sentences, categories 5 and 6, displayed at the whole brain FWE corrected threshold  
922 of  $p < 0.05$  also displayed in Figure 3A. (B) The dynamics of permanence-related  
923 interactions. Four models of RSC-medial temporal lobe (MTL) interactions were  
924 compared in a DCM analysis (bottom) with their corresponding exceedance  
925 probabilities (above). Model 3 was the winning model, suggesting RSC and MTL  
926 mutually modulated each other's activity when an imageable sentence involved  
927 something permanent, with input to the system coming through RSC.

	Permanent	Transient
Landmarks	<b>'Everybody uses the village post-box'</b> 1	<b>'People walk past the pile of rubbish'</b> 2
Actions	<b>'The chef always creates complex dinners'</b> 3	<b>'The drummer misses some performances'</b> 4
Abstract	<b>'Humans are capable of enduring friendships'</b> 5	<b>'The climate is constantly changing'</b> 6

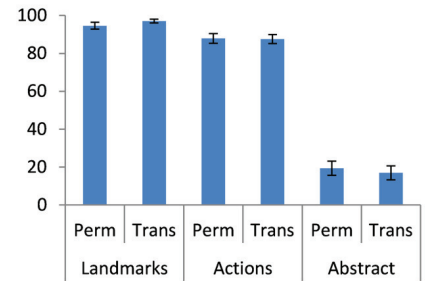
**% Sentences regarded as 'ordinary'**



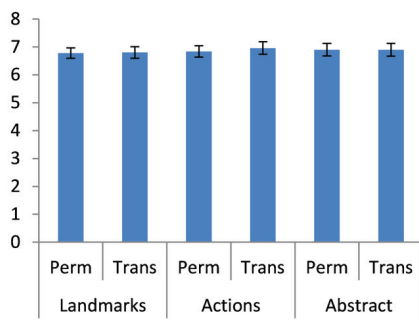
**% Sentences where anything else came to mind**



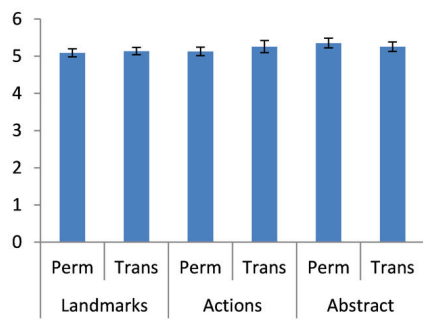
**% Sentences which brought an image to mind**



**Mean number of words**



**Mean word length**



**Mean word frequency**

