Please cite this article in press as: Wolbers et al., Modality-Independent Coding of Spatial Layout in the Human Brain, Current Biology (2011), doi:1 0.101 6/j.cub.2011.04.038

Current Biology 21,1–6, June 7, 2011 ©2011 Elsevier Ltd All rights reserved DOI 10.1016/j.cub.2011.04.038

Report

# Modality-Independent Coding of Spatial Layout in the Human Brain

Thomas Wolbers,[1,6,*] Roberta L. Klatzky,[2] Jack M. Loomis,[3] Magdalena G. Wutte,[4] and Nicholas A. Giudice[5,6,*]

[1]Centre for Cognitive and Neural Systems, University of Edinburgh, Edinburgh EH8 9JZ, UK

[2]Department of Psychology, Carnegie Mellon University, Pittsburgh, PA 15213, USA

[3]Department of Psychology, University of California at Santa Barbara, Santa Barbara, CA 93106, USA

[4]Graduate School of Systemic Neurosciences, Ludwig-Maximilians University, 80539 Munich, Germany [5]Department of Spatial Information Science and Engineering, University of Maine, Orono, ME 04469-5711, USA

## Summary

In many nonhuman species, neural computations of navigational information such as position and orientation are not tied to a specific sensory modality [1, 2]. Rather, spatial signals are integrated from multiple input sources, likely leading to abstract representations of space. In contrast, the potential for abstract spatial representations in humans is not known, because most neuroscientific experiments on human navigation have focused exclusively on visual cues. Here, we tested the modality independence hypothesis with two functional magnetic resonance imaging (fMRI) experiments that characterized computations in regions implicated in processing spatial layout [3]. According to the hypothesis, such regions should be recruited for spatial computation of 3D geometric configuration, independent of a specific sensory modality. In support of this view, sighted participants showed strong activation of the parahippocampal place area (PPA) and the retrosplenial cortex (RSC) for visual and haptic exploration of information-matched scenes but not objects. Functional connectivity analyses suggested that these effects were not related to visual recoding, which was further supported by a similar preference for haptic scenes found with blind participants. Taken together, these findings establish the PPA/RSC network as critical in modality-independent spatial computations and provide important evidence for a theory of high-level abstract spatial information processing in the human brain.

## Results

To test our hypothesis that the human brain would show modality-independent responses to spatial layout, we used functional magnetic resonance imaging (fMRI) while presenting participants with a modified version of a paradigm previously shown to activate scene-sensitive regions in sighted humans [4]. Specifically, we used Lego bricks to construct (1) 27 indoor scenes that were matched in size and complexity but differed with respect to their geometric properties and (2) 27 abstract geometric objects. We then administered a delayed matching-to-sample (DMTS) task that required participants to compare the spatial layout of four sequentially presented stimuli to a final sample stimulus (Figure 1). This behavioral task was administered separately in two versions, a visual version during which subjects saw grayscale photographs of the stimuli and a haptic version during which they acquired the geometric structure of the stimuli via exploration with the right hand.

### Spatial Layout Processing in Sighted Subjects

Whereas reaction times in the visual version of the DMTS task did not differ between objects and scenes ($p > 0.5$), the parahippocampal place area (PPA) (identified in each subject with a functional localizer; see Supplemental Experimental Procedures available online) responded more vigorously when subjects were attending to the geometric structure of indoor scenes than objects ($t = 10.22$, $p < 0.001$, $d = 1.92$; Figure 2A). Importantly, activation differences between objects and scenes did not correlate with differences in reaction time (left PPA: $r = -0.21$, $p > 0.5$; right PPA: $r = -0.64$, $p > 0.1$) or accuracy (left PPA: $r = 0.29$, $p > 0.5$; right PPA: $r = 0.63$, $p > 0.1$), and they did not differ between the right and left PPA ($F = 4.108$, $p = 0.09$; condition by hemisphere interaction: $F = 0.437$, $p = 0.533$). These results replicate previously reported differences between Lego scenes and objects in the PPA during passive viewing and during a continuous one-back task [4]. Voxel-wise whole-brain analyses revealed similar effects in retrosplenial cortex (RSC) and in the superior frontal gyrus (Table S1). By comparison, the reverse contrast (objects > scenes) did not reveal any significant results, and we did not observe any voxels that showed a significant correlation with behavioral performance.

In the haptic version of the DMTS task, reaction times also did not differ between the two stimulus types ($p > 0.05$), and we observed significantly stronger responses in the PPA when subjects explored the scenes by touch as compared to the objects ($t = 2.45$, $p < 0.05$, $d = 0.40$; Figure 2A). Again, larger activation differences between scenes and objects were not associated with larger differences in reaction time (left PPA: $r = -0.32$, $p > 0.4$; right PPA: $r = 0.25$, $p > 0.5$) or accuracy (left PPA: $r = -0.59$, $p > 0.1$; right PPA: $r = -0.02$, $p > 0.5$), and treating the right and left PPA as separate regions of interest (ROI) did not reveal a main effect of hemisphere ($F = 0.009$, $p = 0.93$) or an interaction between task and hemisphere ($F = 1.753$, $p = 0.23$). These results demonstrate that coding for spatial layout in the PPA can be driven by modalities other than vision. In addition, because the match and sample stimuli differed with respect to the presence of furniture and toy characters (see Supplemental Information), we reran our analyses while only focusing on the sample stimuli. These analyses replicated all the results reported for the sighted and the blind participants (see below); hence, only the results from the analyses that included the match stimuli are reported here.

Given that (1) haptic experiences can be recoded into visual mental images [5] and (2) visual imagery of scenes can elicit both occipital and PPA responses [6], the PPA responses

[6]These authors contributed equally to this work
*Correspondence: twolbers@ed.ac.uk (T.W.), giudice@spatial.maine.edu (N.A.G.)

Please cite this article in press as: Wolbers et al., Modality-Independent Coding of Spatial Layout in the Human Brain, Current Biology (2011), doi:1 0.101 6/j.cub.2011.04.038



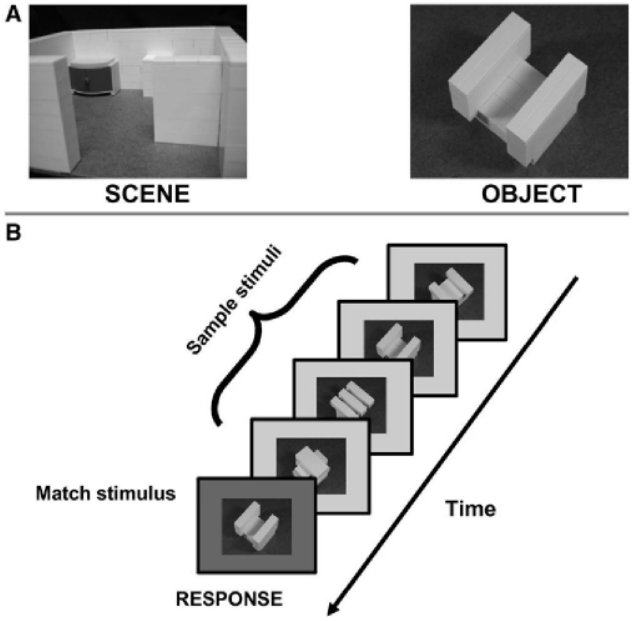



Figure 1. Experimental Paradigm of the Delayed Matching-to-Sample Task
We constructed 27 scenes and 27 objects with different geometric layouts. To make the rooms distinguishable, we manipulated the number, size, and position of the interior walls, thereby giving each room a unique geometric layout. Because the PPA is believed to represent navigable spatial layouts in which one can move about [2], the scenes also contained toy characters and small furniture. In addition, we acquired digital images of each room and each object and rendered them in grayscale. In the visual condition, stimuli were displayed as photographs on a screen inside the bore of the MRI scanner. Six blocks of objects and six blocks of rooms were presented in alternating order, with intervening rest periods (duration 16 s) during which subjects fixated a white cross on a black background. In the haptic condition, the physical models were placed on a tray positioned on the upper right thigh, and participants explored the stimuli with the right hand. For further information about the stimuli, see Figure S1.
(B) Each trial started with the presentation of four sample stimuli, followed by a fifth stimulus, the match stimulus (shown here for the object scenario). In the case of scenes, furniture was removed from this final match stimulus to emphasize that the geometric properties were the relevant dimension. In the visual task, each image was shown for 3 s, followed by a 1 s interstimulus interval (ISI). In the haptic task, each stimulus was presented for 12 s, followed by a 4 s ISI. Participants decided with a two-alternative forced-choice button press whether or not the geometric structure of the match stimulus was identical to any of the previous four sample stimuli. Six blocks of objects and six blocks of rooms were presented in alternating order, with the initial block type randomized across participants.

that we observed during haptic exploration could, in principle, reflect a visual representation of scene geometry. Visual information reaches the posterior parahippocampus via direct projections from multiple occipital regions [7, 8]; hence we addressed this recoding hypothesis with functional connectivity analyses. Specifically, for both DMTS tasks, we tested whether occipital regions showed a scene-specific increase in coupling with the PPA (collapsed across hemispheres). In contrast to the visual task, we did not observe any significant voxels in the haptic task, indicating that the covariation between occipital and PPA responses did not differ between scene and object blocks during haptic exploration. Direct comparisons supported these findings by revealing multiple clusters in occipital cortex in which the scene-related increase in coupling with the PPA was significantly stronger under visual than haptic stimulation (Figure 2B; Table S2).

## Spatial Layout Processing in Blind Subjects

Experiment 1 suggests that scene-selective responses in the human brain can be driven by modalities other than vision. Given the absence of context-dependent coupling between occipital cortex and the PPA during haptic exploration, these results are unlikely to arise from occipital processing during nonvisual stimulation, which would have been indicative of mental imagery. However, because occipital activation has not always been reported in studies on mental imagery [9], we performed a second, complementary test of the recoding hypothesis with age- and gender-matched blind participants. Analogous PPA/RSC involvement in the blind participants would rule out the possibility of recoding based on visual experience and provide evidence for multimodal processing of spatial layout.

Like the sighted participants, those who were blind responded as quickly to scene stimuli as to objects ($p > 0.1$). Because a paradigm to localize the PPA in blind subjects has yet to be established, we followed a previously established approach [10] and used the group results from the functional localizer task in the sighted subjects to define an average PPA ROI for the blind participants (Figure 3). As Figure 3 demonstrates, activation profiles in the blind participants were highly similar to the sighted: blood oxygenation level dependent (BOLD) responses were significantly greater when subjects haptically explored the scenes than when they explored objects ($t = 4.19$, $p < 0.01$, $d = 0.62$) but did not differ between the right and left PPA (main effect of hemisphere: $F = 0.07$, $p = 0.80$; task by hemisphere interaction: $F = 1.26$, $p = 0.30$). Moreover, differences in BOLD responses did not correlate with differences in reaction time (left PPA: $r = 0.32$, $p > 0.4$; right PPA: $r = 0.32$, $p > 0.4$) or accuracy (left PPA: $r = 0.54$, $p > 0.2$; right PPA: $r = 0.13$, $p > 0.5$). Outside the PPA, both groups showed stronger bilateral activation for haptic exploration of scenes in RSC (Figure 4; Table S1); however, in the left hemisphere, the cluster of significant voxels extended into the parieto-occipital sulcus. Similar results were observed in area 7p [11] of the superior parietal lobe and in the middle frontal gyrus. Because the RSC appeared to show deactivation for objects in the blind subjects, we tested for a negative effect but did not observe any significant voxels in the sighted or the blind subjects. Importantly, we did not observe differences between scenes and objects in primary motor cortex, suggesting that the amount of motor exploration did not differ between stimuli. Furthermore, the reverse analysis (objects > scenes) did not reveal any significant effects, and we did not observe any voxels that showed a significant correlation with behavioral performance.

Finally, we tested for overlapping and differential responses between sighted and blind participants with a whole-brain analysis on the haptic task. A conjunction analysis [12] revealed that both blind and sighted participants recruited a large network of regions during haptic exploration of scenes and objects, with the maximum responses in areas implicated in motor control and sensorimotor processing (Table S5). In addition, although blind and sighted subjects did not differ in their overall reaction times ($F = 0.054$, $p > 0.5$), blind subjects exhibited stronger activation in occipital and middle temporal areas (Table S2). These findings support previous reports showing that blind humans recruit occipitotemporal cortices during tactile exploration of objects [13,14] and Braille reading [15, 16]. However, similar to the sighted participants, a functional connectivity analysis did not reveal any clusters in

Please cite this article in press as: Wolbers et al., Modality-Independent Coding of Spatial Layout in the Human Brain, Current Biology (2011), doi:1 0.101 6/j.cub.2011.04.038



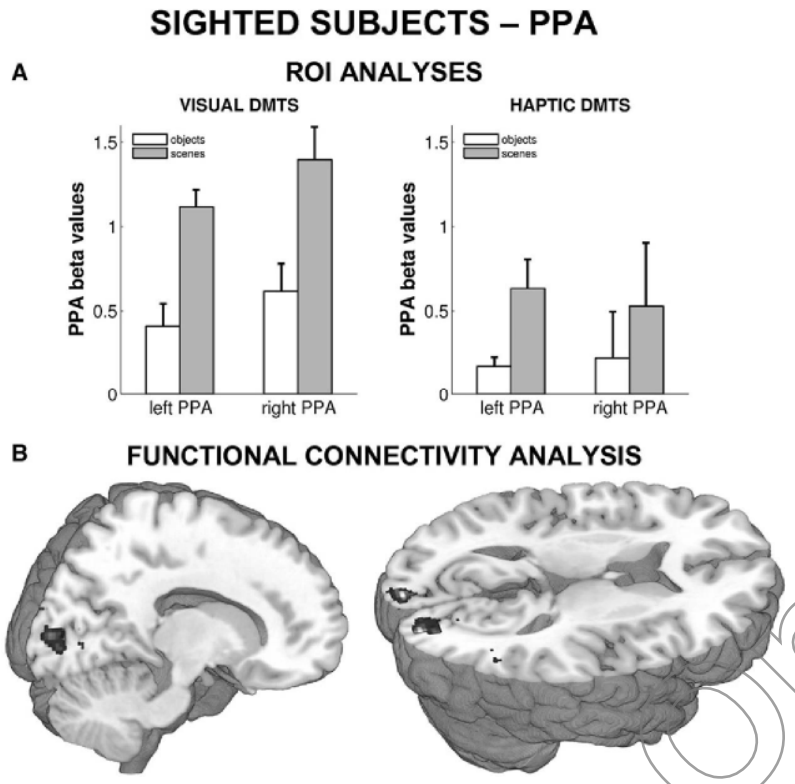



Figure 2. Modality-Independent Scene Processing in the PPA of Sighted Subjects

(A) In the visual version of the delayed matching-to-sample task, the PPA responded more strongly when subjects were viewing and memorizing scenes as compared to objects (left). Similar results were observed in the haptic condition (right) when subjects manually explored the stimuli. For each subject and condition, we extracted the responses for scenes and objects and averaged them across all voxels in the individual PPA regions of interest (as identified by the functional localizer). The graph shows the mean activations (+ standard error of the mean [SEM]) in the PPA averaged across participants. Effect sizes for the differences between scenes and objects were as follows: visual DMTS: left PPA (d = 1.68), right PPA (d = 1.57); haptic DMTS: left PPA (d =1.21), right PPA (d = 0.29). See Table S1 for additional whole-brain analyses and Figure S2 for data from individual subjects.

(B) Given that the PPA receives direct projections from various occipital areas, we performed functional connectivity analyses with the PPA as a seed region to identify voxels whose activation showed a stronger covariation with the PPA during scene than during object blocks. After performing this analysis separately for the visual and the haptic DMTS task, a paired t test revealed multiple clusters in occipital cortex in which the context-dependent coupling was significantly stronger during visual than during haptic stimulation. To show the subthreshold extent of the effect, we displayed the results of the random-effects analysis on the MNI template brain with a threshold of $p < 0.001$ uncorrected. See Table S2 for complete voxelwise statistics.

occipital cortex that showed a stronger covariation with the PPA during scene than during object blocks.

## Discussion

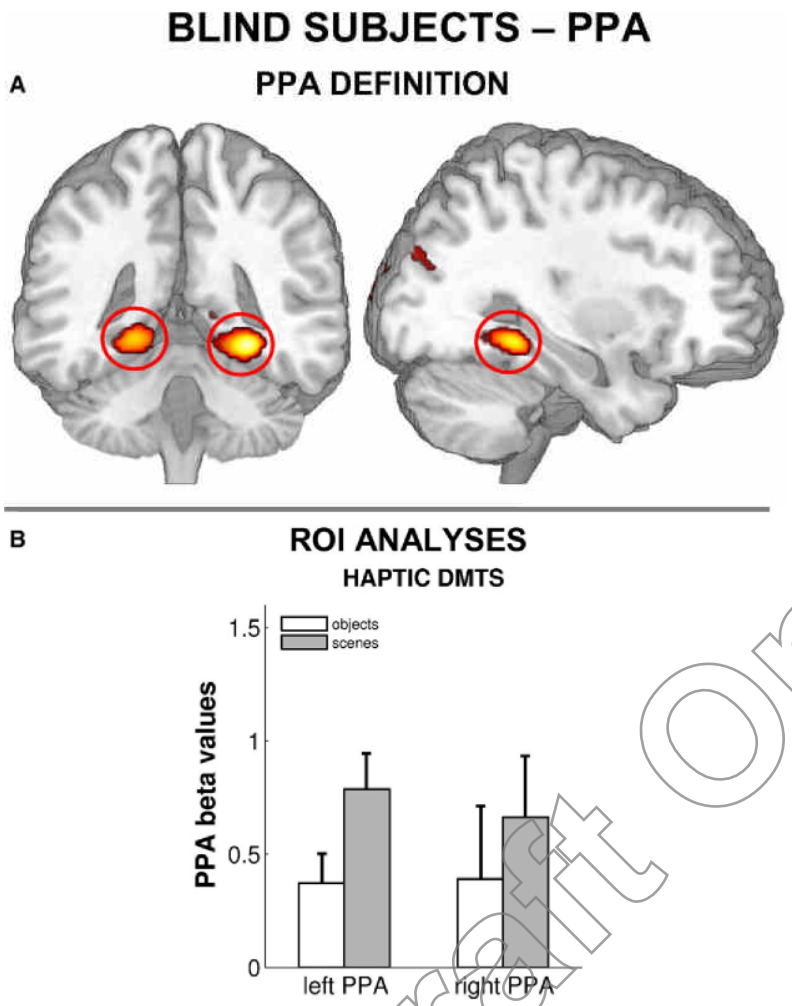
These studies investigated whether regions such as the PPA and the RSC can be recruited for computation of spatial layout, independent of a specific sensory modality. In experiment 1, sighted subjects showed stronger PPA/RSC responses for visually presented scenes than for objects, which replicates previous findings. Similar differences were observed when stimuli were apprehended via haptic exploration, suggesting a targeted network that can be driven both by visual and nonvisual spatial information. Importantly, functional connectivity analyses and a similar PPA/RSC preference for scenes in blind participants showed that these effects were not related to a recoding of haptic experiences into visually dependent mental images. Taken together, our findings strongly support a theory of modality-independent coding of spatial layout in the brain, which adds to the growing evidence for multimodal coding in other specialized processing regions such as the fusiform face area [17,18] or the object-sensitive ventral visual pathway [10,19].

Although previous research on the spatial functions of the PPA and RSC has focused on visual processing, spatial information can be acquired and represented from multiple nonvisual sources [20]. For example, in rodents, position signals in place and grid cells and orientation signals in head direction cells not only are sensitive to visual landmarks but also can be updated by body-based cues when the animal moves around in darkness [1, 2]. In addition, human behavioral studies suggest that both visual and nonvisual cues influence our navigational behavior [21–24]. Taken together, this evidence indicates that various types of spatial information can be acquired from different sensory modalities and ultimately represented in a common, modality-independent format, thus supporting mental computations and spatial behaviors independent of the input source. This hypothesis has been elaborated in several ways, including the spatial representation system [25], the spatial image [26], and the notion of metamodal brain organization [27].

The present results extend this claim by showing that the scene-specific responses in the human brain are not restricted to visual input but can also arise from haptic exploration. Our findings are parallel to those of Mahon et al. [10], who showed that preferences for object categories in the ventral visual stream do not require visual experience. Here, when scenes and objects were presented as grayscale photographs to the sighted subjects, we observed the well-established PPA preference for scenes. When corresponding information was acquired from haptic exploration of the physical models, a similar PPA preference for scenes emerged. Although this effect could have been driven by a recoding of haptic experiences into visual mental images, this account appears unlikely for two reasons. First, the coupling between occipital cortex and the PPA was selectively enhanced during visually presented scene blocks, which argues against an imagery-related occipital contribution. Second, we observed the same PPA selectivity for scenes in blind participants during haptic exploration. Although the definition of the PPA in the blind bears some anatomical uncertainty—as a result of the absence of an established functional localizer for this population—our data suggest that the PPA intrinsically functions to represent spatial layout in a format that is not tied to a specific sensory modality.

Please cite this article in press as: Wolbers et al., Modality-Independent Coding of Spatial Layout in the Human Brain, Current Biology (2011), doi:1 0.101 6/j.cub.2011.04.038






(A) Given the absence of a functional PPA localizer for blind subjects, we defined the PPA based on the results from the functional localizer task in sighted subjects. The panels show the results of a fixed-effects analysis in the sighted subjects that tested for differences between scenes and objects. Results are displayed on the MNI template brain, using a threshold of $p < 0.05$ corrected for multiple comparisons. For each of the blind subjects, we extracted the responses for scenes and objects and averaged them across all voxels in the right and left PPA.

(B) In the haptic version of the task, blind participants showed stronger PPA activation for scenes than for objects, thus replicating the results of the sighted subjects. The graph shows the mean activations (+SEM) in the PPA ROIs, averaged across participants. Effect sizes for the differences between scenes and objects were as follows: left PPA ($d = 1.04$), right PPA ($d = 0.28$). For detailed demographic data on the blind participants, see Table S3.

In addition to the PPA, we observed stronger responses to scenes in RSC, independent of the encoding modality. Although several proposals exist with regard to the precise navigational functions of the RSC [28–30], our tasks are fully consistent with studies reporting strong RSC responses to unfamiliar scenes that provide ample geometric information [29]. Our results show for the first time that scene sensitivity in the RSC, as in the PPA, is not restricted to the visual modality but also emerges when spatial layout information is acquired from haptic experiences. Given the extensive network of afferent projections to the RSC [31], it therefore appears likely that various streams of spatial information processing converge in the RSC to support the encoding, storage, and manipulation of spatial layout information.

In both the PPA and the RSC, the overall activation and the scene-specific increases were weaker in the haptic than in the visual condition. These differences are likely related to differences in sensory processing: haptic input is slower to apprehend, as a result of serial versus parallel encoding, and tactile resolution and bandwidth capacity are far lower than that of vision [32]. As such, one would expect it to be a slower and noisier signal to use for building up a scene representation. Behavioral findings support this assumption because visual maps are faster to learn and yield less overall variability at testing than the same learning and testing from haptic maps, but both input modalities show an almost identical pattern of speed and error performance on spatial updating tasks [33]. These results indicate the building up and accessing of a multimodal representation, which is consistent with our findings of the PPA and the RSC processing information from multiple input sources. Importantly, future studies—potentially using intracortical recordings—are needed to ultimately verify the idea that identical neuronal populations are driven by visual and haptic inputs.

In conclusion, we have shown that the PPA and the RSC, two key regions of the human spatial navigation network [3], respond both to visual and haptic presentation of spatial layouts. Together with the multisensory properties of other spatial systems such as the head direction, grid, and place cell networks, our findings provide further evidence for the notion that the mammalian brain may code for spatial information in a format that is not tied to a specific sensory modality. Given that spatial properties (size, distance, direction, etc.) are fundamental dimensions of the physical world that do not require a specific type of sensory processing, it is tempting to speculate that cortical systems have evolved to construct this abstract format.

## Experimental Procedures

### Subjects

Eight healthy volunteers (six right-handed, one ambidextrous according to [34], and one unknown), all with normal or corrected-to-normal vision, participated in experiment 1, and eight blind volunteers (all right-handed Braille readers), matched for age and sex, participated in experiment 2. Because one blind participant in experiment 2 had to be removed because of excessive head movement, we removed the corresponding sighted subject as well. Therefore, the final data sets comprised seven sighted subjects (two female, age range 22–77 yrs) and seven blind subjects (two female, age range 22–75 yrs). See Table S3 for further information on the etiology and age of onset of blindness.

### Image Processing and Statistical Analysis of fMRI Data

Image processing and statistical analysis were carried out using SPM8 (Wellcome Department of Imaging Neuroscience, London). All volumes

Figure 3. Haptic Scene Processing in the PPA of Blind Subjects

Please cite this article in press as: Wolbers et al., Modality-Independent Coding of Spatial Layout in the Human Brain, Current Biology (2011), doi:1 0.101 6/j.cub.2011.04.038



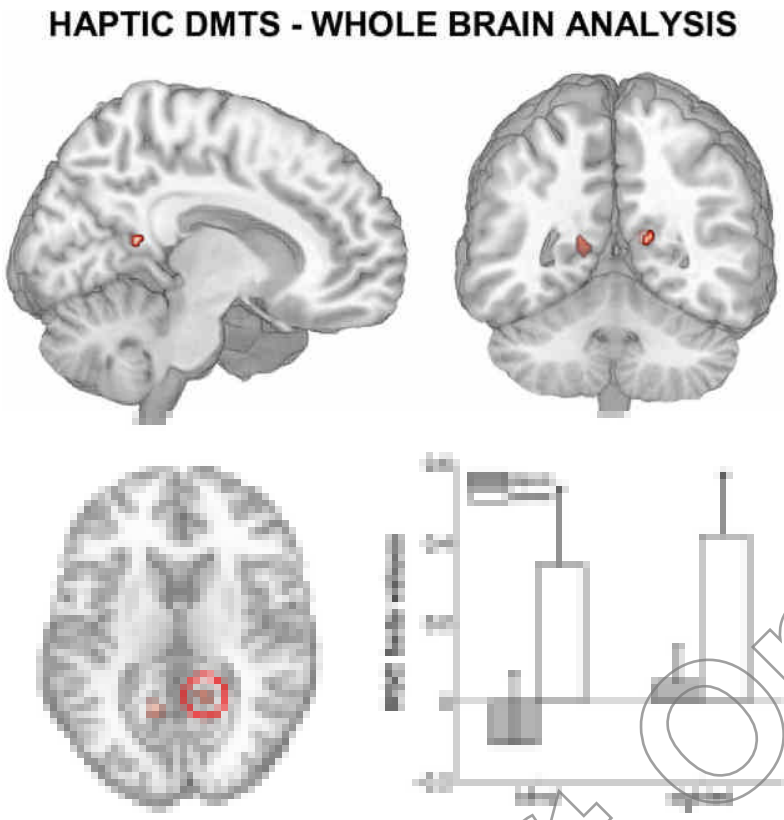



Figure 4. Haptic Scene Processing in Retrosplenial Cortex

Whole-brain analysis showing regions beyond the PPA that responded more strongly to haptic exploration of scenes than objects in both groups. Consistent with our findings on visual processing, bilateral effects were observed in retrosplenial cortex, and scene selectivity did not differ between blind and sighted participants. In all panels, results of the random-effects analysis are displayed with a threshold of $p < 0.05$ corrected for multiple comparisons. The lower right panel shows the mean activations (+SEM) of all voxels in the right retrosplenial cortex, averaged across participants. Similar results were obtained in superior parietal cortex and middle frontal gyrus (see Table S4). For further activations common to both subject groups, see Table S5. For signal time courses from the RSC and the PPA, see Figure S4.



were realigned to the first volume, spatially normalized to an Echo Planar Imaging (EPI) template in a standard coordinate system [35], and finally smoothed using a 9 mm full-width at half-maximum isotropic Gaussian kernel.

In the sighted subjects, we identified the PPA in each subject with a functional localizer task (see Supplemental Experimental Procedures). We also performed a whole-brain fixed-effects analysis across all sighted subjects to define a PPA ROI for the blind subjects, given the absence of an established PPA localizer for this population. We then estimated statistical models for the DMTS tasks in the PPA ROIs of each participant and entered the resulting parameter estimates into paired t tests. To test for regions outside the PPA showing differences between objects and scenes, we performed whole-brain random-effects analyses as implemented in SPM8. The functional connectivity analyses were performed with the functional connectivity toolbox (http://web.mit.edu/swg/software.htm)—one for the visual and one for the haptic condition—to identify voxels in occipital cortex whose activation showed a stronger covariation with the PPA during scene than during object blocks. Detailed information about experimental procedures, MRI acquisition, image processing, and statistical analysis of fMRI data is given in the Supplemental Experimental Procedures.

## Supplemental Information

Supplemental Information includes six figures, one table, and Supplemental Experimental Procedures and can be found with this article online at doi:10.1016/j.cub.2011.04.038.

## Acknowledgments

This work was supported by a University of California at Santa Barbara faculty research grant to J.M.L., National Science Foundation grant BCS-0745328, and National Institutes of Health grant R01-EY016817 (J.M.L., PI). M.G.W. was supported by a travel grant from the Graduate School for Systemic Neuroscience, Munich. We also would like to thank LEGO Systems for providing the material for the construction of the experimental stimuli and Brendan McHugh and Masaki Miyanohara for help with conducting the experiments.

Received: November 19, 2010
Revised: February 14, 2011
Accepted: April 21, 2011
Published online: May 26, 2011

## References

1. Jeffery, K.J. (2007). Self-localization and the entorhinal-hippocampal system. Curr. Opin. Neurobiol. 17, 684–691.
2. Taube, J.S. (2007). The head direction signal: Origins and sensory-motor integration. Annu. Rev. Neurosci. 30,181–207.
3. Epstein, R.A. (2008). Parahippocampal and retrosplenial contributions to human spatial navigation. Trends Cogn. Sci. (Regul. Ed.) 12,388–396.
4. Epstein, R., Harris, A., Stanley, D., and Kanwisher, N. (1999). The parahippocampal place area: Recognition, navigation, or encoding? Neuron 23,115–125.
5. Newell, F.N., Woods, A.T., Mernagh, M., and Bu¨lthoff, H.H. (2005). Visual, haptic and crossmodal recognition of scenes. Exp. Brain Res. 161, 233–242.
6. O'Craven, K.M., and Kanwisher, N. (2000). Mental imagery of faces and places activates corresponding stiimulus-specific brain regions. J. Cogn. Neurosci. 12,1013–1023.
7. Gattas, R., Sousa, A.P., Mishkin, M., and Ungerleider, L.G. (1997). Cortical projections of area V2 in the macaque. Cereb. Cortex 7, 110–129.
8. Ungerleider, L.G., Galkin, T.W., Desimone, R., and Gattass, R. (2008). Cortical connections of area V4 in the macaque. Cereb. Cortex 18, 477–499.
9. Mellet, E., Petit, L., Mazoyer, B., Denis, M., and Tzourio, N. (1998). Reopening the mental imagery debate: Lessons from functional anatomy. Neuroimage 8, 129–139.
10. Mahon, B.Z., Anzellotti, S., Schwarzbach, J., Zampini, M., and Caramazza, A. (2009). Category-specific organization in the human brain does not require visual experience. Neuron 63, 397–405.
11. Scheperjans, F., Hermann, K., Eickhoff, S.B., Amunts, K., Schleicher, A., and Zilles, K. (2008). Observer-independent cytoarchitectonic mapping of the human superior parietal cortex. Cereb. Cortex 18, 846–867.

12. Nichols, T., Brett, M., Andersson, J., Wager, T., and Poline, J.B. (2005). Valid conjunction inference with the minimum statistic. Neuroimage 25, 653–660.
13. Amedi, A., Jacobson, G., Hendler, T., Malach, R., and Zohary, E. (2002). Convergence of visual and tactile shape processing in the human lateral occipital complex. Cereb. Cortex 12,1202–1212.
14. Pietrini, P., Furey, M.L., Ricciardi, E., Gobbini, M.I., Wu, W.H., Cohen, L., Guazzelli, M., and Haxby, J.V. (2004). Beyond sensory images: Object-based representation in the human ventral pathway. Proc. Natl. Acad. Sci. USA 101, 5658–5663.
15. Hamilton, R.H., and Pascual-Leone, A. (1998). Cortical plasticity associated with Braille learning. Trends Cogn. Sci. (Regul. Ed.) 2,168–174.
16. Bu¨chel, C., Price, C., Frackowiak, R.S.J., and Friston, K. (1998). Different activation patterns in the visual cortex of late and congenitally blind subjects. Brain 121,409–419.
17. Kilgour, A.R., Kitada, R., Servos, P., James, T.W., and Lederman, S.J. (2005). Haptic face identification activates ventral occipital and temporal areas: An fMRI study. Brain Cogn. 59,246–257.
18. Kitada, R., Johnsrude, I.S., Kochiyama, T., and Lederman, S.J. (2009). Functional specialization and convergence in the occipito-temporal cortex supporting haptic and visual identification of human faces and body parts: An fMRI study. J. Cogn. Neurosci. 21, 2027–2045.
19. James, T.W., Humphrey, G.K., Gati, J.S., Servos, P., Menon, R.S., and Goodale, M.A. (2002). Haptic study of three-dimensional objects activates extrastriate visual areas. Neuropsychologia 40,1706–1714.
20. Wolbers, T., and Hegarty, M. (2010). What determines our navigational abilities? Trends Cogn. Sci. (Regul. Ed.) 14,138–146.
21. Loomis, J.M., Klatzky, R.L., Golledge, R.G., Cicinelli, J.G., Pellegrino, J.W., and Fry, P.A. (1993). Nonvisual navigation by blind and sighted: Assessment of path integration ability. J. Exp. Psychol. Gen. 122, 73–91.
22. Tcheang, L., Bu¨lthoff, H.H., and Burgess, N. (2011). Visual influence on path integration in darkness indicates a multimodal representation of large-scale space. Proc. Natl. Acad. Sci. USA 108, 1152–1157.
23. Nardini, M., Jones, P., Bedford, R., and Braddick, O. (2008). Development of cue integration in human navigation. Curr. Biol. 18, 689–693.
24. Presson, C.C., and Montello, D.R. (1994). Updating after rotational and translational body movements: Coordinate structure of perspective space. Perception 23,1447–1455.
25. Bryant, K.J. (1997). Representing space in language and perception. Mind Lang. 12, 239–264.
26. Loomis, J.M., Lippa, Y., Golledge, R.G., and Klatzky, R.L. (2002). Spatial updating of locations specified by 3-d sound and spatial language. J. Exp. Psychol. Learn. Mem. Cogn. 28, 335–345.
27. Pascual-Leone, A., and Hamilton, R. (2001). The metamodal organization of the brain. In Vision: From Neurons to Cognition. Progress in Brain Research, Volume 134, C. Casanova and M. Ptito, eds. (Amsterdam: Elsevier), pp. 427–445.
28. Byrne, P., and Becker, S. (2004). Modeling mental navigation in scenes with multiple objects. Neural Comput. 16,1851–1872.
29. Henderson, J.M., Larson, C.L., and Zhu, D.C. (2008). Full scenes produce more activation than close-up scenes and scene-diagnostic objects in parahippocampal and retrosplenial cortex: An fMRI study. Brain Cogn. 66, 40–49.
30. Park, S., and Chun, M.M. (2009). Different roles of the parahippocampal place area (PPA) and retrosplenial cortex (RSC) in panoramic scene perception. Neuroimage 47,1747–1756.
31. Kobayashi, Y., and Amaral, D.G. (2003). Macaque monkey retrosplenial cortex: II. Cortical afferents. J. Comp. Neurol. 466,48–79.
32. Loomis, J.M., and Lederman, S.J. (1986). Tactual perception. In Handbook of Perception and Human Performance, Volume 2, K. Boff, L. Kaufman, and J. Thomas, eds. (New York: Wiley).
33. Giudice, N.A., Betty, M.R., and Loomis, J.M. (2011). Functional equivalence of spatial images from touch and vision: Evidence from spatial updating in blind and sighted individuals. J. Exp. Psychol. Learn Mem. Cogn. 37, 621–634.
34. Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia 9, 97–113.
35. Evans, A.C., Collins, D.L., Mills, S.R., Brown, E.D., Kelly, R.L., and Peters, T.M. (1993). 3D statistical neuroanatomical models from 305 MRI volumes In Nuclear Science Symposium & Medical Imaging Conference: 1993 IEEE Conference Record, L. Klaisner, ed., pp. 1813–1817.

**Current Biology, Volume *21***

# Supplemental Information

# Modality-Independent Coding of Spatial Layout in the Human Brain

**Thomas Wolbers, Roberta L. Klatzky, Jack M. Loomis, Magdalena G. Wutte, and Nicholas A. Giudice**

## Supplemental Inventory

1. **Supplemental Figures and Tables**

   Figure S1, related to Figure 1

   Figure S2, related to Figure 2

   Figure S3, related to Figure 4

   Table S1, related to Figure 2

   Table S2, related to Figure 2

   Table S3, related to Figure 3

   Table S4, related to Figure 4

   Table S5, related to Figure 4

2. **Supplemental Experimental Procedures**
3. **Supplemental References**

**Figure S1, related to Figure 1.**
Representative floor plans and screenshots of the scene stimuli.

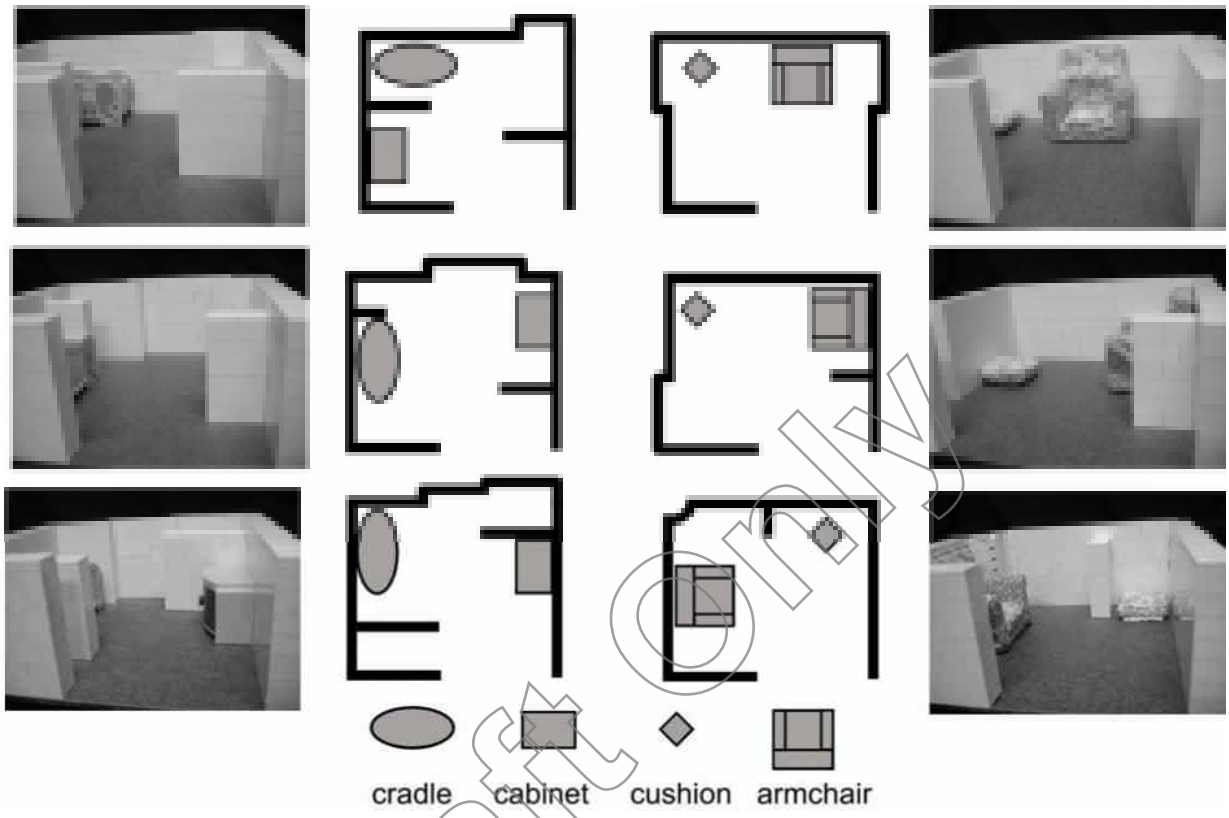


**Figure S2, related to Figure 2.**
Single subject data showing the difference in PPA activation between scenes and objects for the different tasks / groups. In the visual condition, stronger PPA responses to scenes vs. objects were seen in all sighted subjects. In the haptic task, 6 out of the 7 sighted and 7 out of the 7 blind subjects showed the same effect, albeit when compared to the visual task, the magnitude of the response differences was smaller for most participants.

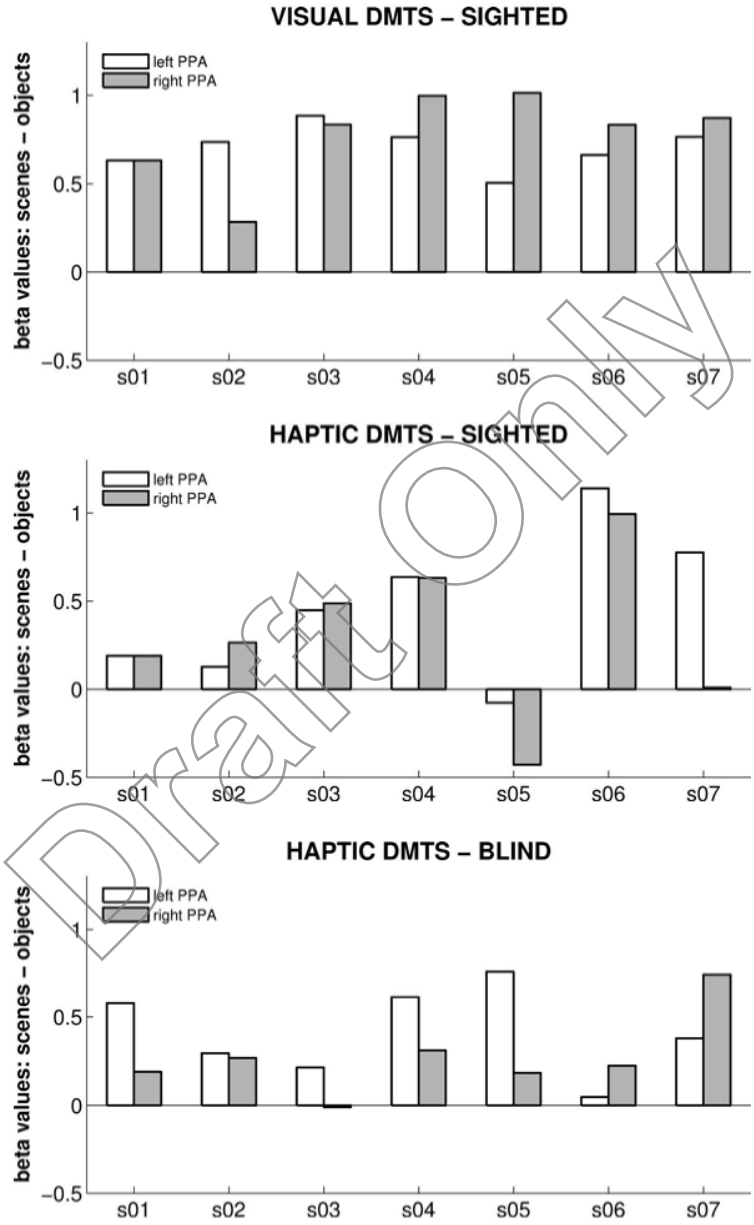


**Figure S3, related to Figure 4.**
Averaged time courses (+/- sem) for the haptic DMTS task for the left PPA, the right PPA and the RSC. For the PPA, time courses were calculated by averaging across all voxels in the subject specific PPA-ROI's. For the RSC, time courses were calculated by averaging across all voxels in retrosplenial cortex as identified by the whole brain analysis that included both groups (see Figure 4). The plots are aligned with the presentation of the first stimulus in a block and cover the entire duration of a block.

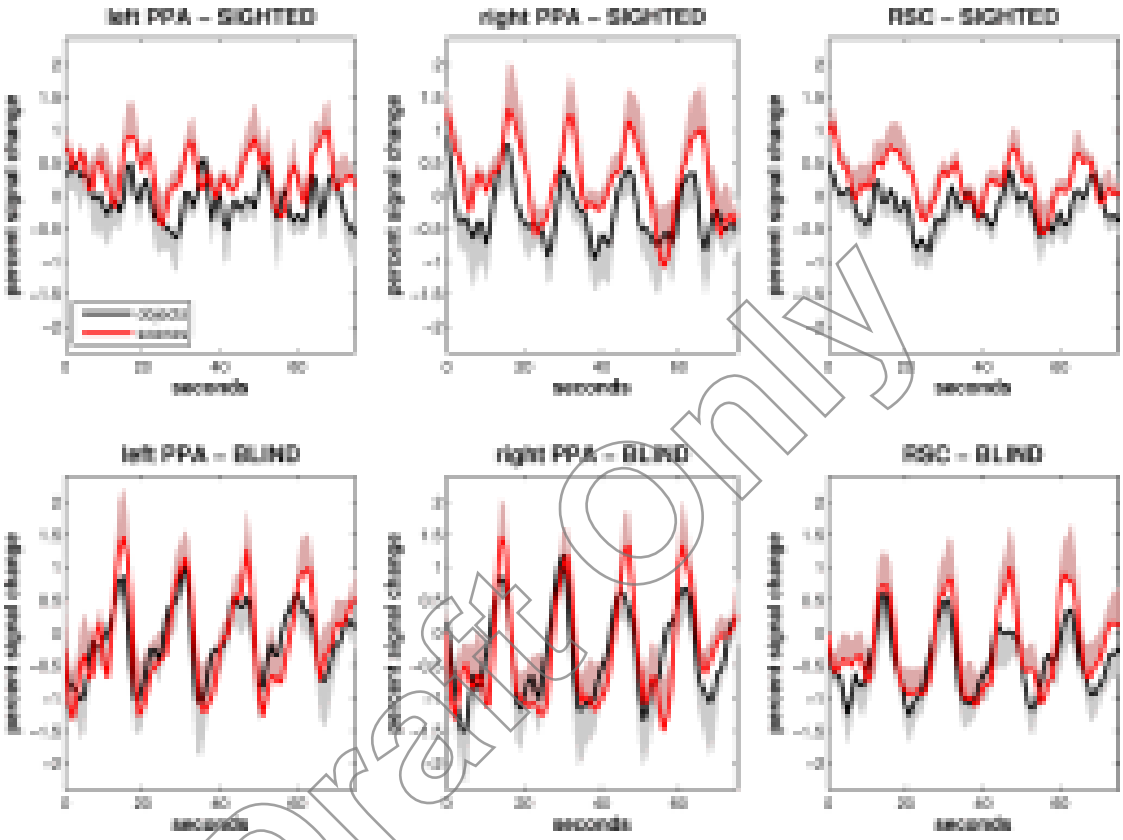


**Table S1. Whole Brain Analyses for the Visual DMTS Task in the Sighted. Related to Figure 2**

| Spatial coordinates of the local maxima | | |
|---|---|---|
| Region | Coordinate (x, y, z, in mm) | Voxel-level (t-score) |
| | LH RH | |
| ***Contrast: scenes > objects*** | | |
| Retrosplenial cortex | 10, -54, 12 | 46.44 |
| Superior frontal gyrus | 22, -2, 64 | 34.65 |
| ***Contrast: objects > scenes*** | | |
| No significant voxels | | |

RH/LH – right/left hemisphere; threshold: p<0.05 corrected

**Table S2. Functional Connectivity Analyses in Sighted Subjects. Related to Figure 2**

| Spatial coordinates of the local maxima in occipital cortex showing a stronger coupling with the PPA for scene than for object stimuli | | | |
|---|---|---|---|
| Region | Coordinate (x, y, z, in mm) | | Voxel-level (t-score) |
| | LH | RH | |
| **Visual DMTS > Haptic DMTS** | | | |
| Calcarine gyrus | -8, -94, 12 | | 11.79 |
| Superior occipital gyrus | -10, -94, 18 | | 13.54 |
| | | 16, -96, 24 | 12.65 |
| Inferior occipital gyrus | | 38, -72, -10 | 9.69 |
| Cuneus | -10, -92, 16 | | 18.98 |
| **Haptic DMTS > Visual DMTS** | | | |
| No significant voxels | | | |

RH/LH – right/left hemisphere; threshold: p<0.05 corrected

**Table S3. Demographic Information on the Blind Participants. Related to Figure 3**

| Sex | Etiology | age of onset | years blind | Residual Vision |
|---|---|---|---|---|
| M | Retinitis Pigmentosa | birth | 54 | None |
| F | Cancer | 6 months | 22 | None |
| M | Retinitis Pigmentosa | 24 | 25 | None |
| M | Lebers Congenital Amaurosis | birth | 34 | light perception |
| M | Retinopathy of Prematurity | birth | 62 | None |
| F | Retinitis Pigmentosa | 35 | 16 | light and near shape perception |
| M | Optic Nerve Atrophy | 25 | 50 | None |

**Table S4. Main Effects of Task and Group in the Haptic DMTS Task. Related to Figure 4**

Spatial coordinates of the local maxima

| Region | Coordinate (x, y, z, in mm) | | Voxel-level (t-score) |
|---|---|---|---|
| | LH | RH | |
| ***Blind > Sighted (pooled across scenes and objects)*** | | | |
| Superior parietal lobe | | 36, -56, 62 | 10.27 |
| Precuneus | | 10, -78, 48 | 9.03 |
| Cuneus | -14, -88, 38 | | 10.81 |
| Middle temporal gyrus | -42, -62, 2 | | 9.35 |
| Superior occipital gyrus | -24, -88, 28 | | 11.51 |
| | | 24, -84, 34 | 9.09 |
| Middle occipital gyrus | -26, -90, 18 | | 8.94 |
| ***Scenes > Objects (pooled across blind and sighted participants)*** | | | |
| Retrosplenial cortex | -14, -56 10 | | 9.86 |
| | | 14, -50, 14 | 10.19 |
| Superior parietal lobe (area 7p) | -16, -76, 52 | | 8.45 |
| | | 24, -74, 50 | 11.41 |
| Middle frontal gyrus | -32, 24, 28 | | 8.28 |
| ***Objects > Scenes (pooled across blind and sighted participants)*** | | | |
| No significant voxels | | | |

RH/LH – right/left hemisphere; threshold: $p<0.05$ corrected

**Table S5. Conjunction Analysis: Activation Common to Both Groups during Haptic Exploration of Scenes and Objects. Related to Figure 4**

| Spatial coordinates of the local maxima for the contrast:<br>(scenes sighted & objects sighted) & (scenes blind & objects blind) | | | |
|---|---|---|---|
| Region | Coordinate (x, y, z, in mm) | | Voxel-level (t-score) |
| | LH | RH | |
| Inferior frontal gyrus | | 56, 6, 34 | 10.06 |
| Superior frontal gyrus | -4, -4, 54 | | 12.05 |
| | | 8, 4, 52 | 15.80 |
| Precentral gyrus | -36, -20, 56 | | 37.57 |
| | -54, 2, 38 | | 17.97 |
| | | 24, -8, 54 | 15.91 |
| | | 38, -14, 56 | 13.60 |
| Postcentral gyrus | -60, -22, 32 | | 33.61 |
| | -46, -34, 52 | | 44.98 |
| | | 32, -44, 64 | 33.75 |
| | | 64, -20, 36 | 27.73 |
| Parietal Operculum | -54, -18, 16 | | 20.21 |
| | | 62, -18, 20 | 11.23 |
| Supramarginal gyrus | -52, -30, 48 | | 52.38 |
| | | 64, -24, 26 | 22.88 |
| Superior parietal lobe | -16, -66, 56 | | 22.98 |
| | -14, -52, 68 | | 11.33 |
| | | 24, -64, 60 | 17.78 |
| | | 14, -54, 60 | 11.19 |
| Inferior parietal lobe | -34, -56, 60 | | 17.95 |
| | | 38, -46, 52 | 23.07 |
| Inferior temporal gyrus | -46, -56, -2 | | 18.10 |
| | | 44, -58, -8 | 14.26 |
| Superior occipital gyrus | -22, -78, 36 | | 10.91 |
| | | 26, -68, 26 | 10.92 |
| Cerebellum | -26, -56, -16 | | 19.95 |
| | -32, -50, -18 | | 19.66 |
| | | 22, -48, -20 | 29.60 |
| | | 30, -46, -24 | 24.91 |

RH/LH – right/left hemisphere; threshold: $p<0.05$ corrected

## Supplemental Experimental Procedures

*Experimental Stimuli and Paradigm*

We used Lego blocks to construct 27 abstract geometric objects and 27 indoor scenes (furnished rooms). Previous paradigms have shown that viewing similar Lego stimuli reliably activates the PPA [1]. The outer walls were identical in each room, and the entry door was always located at the same position. To make the rooms distinguishable, we manipulated the number, size, and position of the interior walls, thereby giving each room a unique geometric layout. Because the PPA is believed to represent navigable spatial layouts in which one can move about [2], we added toy characters and small furniture. In addition, we acquired digital images of each room and each object and rendered them in grayscale to eliminate any color differences between stimuli (see Figures 1 and S1 for examples). For the rooms, photographs were taken from a first person perspective through the entry door, applying the same angle for each room (see Figure S 1 for examples).

In experiment 1, sighted subjects first performed a haptic and then a visual version of a delayed matching-to-sample (DMTS) task in which they attended to the geometric structure of the stimuli (Figures 1 + S1). In the visual task, each trial began with a visual presentation of a block of four sample stimuli (four different rooms or four different objects). Each image was shown for 3s, followed by a 1s interstimulus interval. Subjects were instructed to memorize the geometric structure of each sample stimulus and to compare it to the structure of a subsequent match stimulus. Specifically, subjects had to decide whether or not the geometric structure of the match stimulus was identical to any of the four sample stimuli. In the case of rooms, furniture was removed from this final match stimulus to emphasize that the geometric properties were the relevant dimension. Subjects indicated match or no-match by pressing one of two buttons on a keypad. Six blocks of objects and six blocks of rooms were presented in alternating order, with intervening rest periods (duration: 16s) during which subjects fixated a white cross on a black background. Initial block type was randomized across subjects.

In the haptic version of the task, room and object models were placed on a tray positioned on the upper right thigh, and subjects explored the stimuli with the right hand only. We first ran two pilot experiments to establish optimal movement trajectories and temporal periods for exploration. Based on these experiments, each stimulus was presented for 12s, followed by a 4s interstimulus interval (ISI). Given that subjects could not know when a new stimulus had been delivered, an auditory command (delivered via headphones) instructed them to start exploring the current stimulus immediately after the ISI. For the sample stimuli, the instruction was 'explore', for the match stimulus it was 'compare'. As in the visual version of the task, subjects were instructed to memorize the geometric structure of each sample stimulus and to compare it to the structure of a subsequent match stimulus. In order to standardize hand movements across stimuli and subjects, they were instructed to move the hand in one fast, counterclockwise circle first to get a general impression of the geometric structure. Following this initial exploration pattern, they were free to return to whatever parts of the stimulus they felt they needed to explore further with no additional restrictions on hand movement. For the rooms, subjects were also instructed to stay within the interior perimeter of the room and to avoid moving along the outer side of the stimuli. This restriction reduced hand movement and ensured that the same stimulus information was available between the visual and haptic scenes. After exploring the matching stimulus, subjects heard an auditory signal cuing them to press one of two buttons to indicate match or no-match. Six blocks of objects and six blocks of rooms were presented in alternating order, separated by an intervening 16s rest period, with the initial block type randomized across subjects.

Although our formal emphasis in the behavioral pilot studies was on quantifying a temporal measure, it is important to note that none of the participants self-reported being confused between what was a scene and what was an object nor did any report having trouble differentiating the stimuli. Furthermore, during fMRI scanning, auditory instructions informed subjects about the type of stimuli (rooms/objects) to be presented in each block. Thus, there was never any possible confusion whether the haptic stimulus was a scene or an object.

Finally, we localized the parahippocampal place area in each subject individually with a functional localizer. Following previously established procedures [3], we presented 20 color pictures of indoor scenes (furnished rooms) and 20 color pictures of everyday objects (e.g. brush, cup). Each stimulus was shown for 400ms, followed by an interstimulus interval of 480ms. Subjects performed a continuous one-back task by pressing a button whenever two successive images were identical. Stimuli were shown in three blocks of rooms alternating with three blocks of objects, with each block containing 22 items (2 targets) presented in a randomized order. Blocks were separated by rest periods (duration: 16s) during which subjects fixated a white cross on a black background.
In experiment 2, the blind subjects performed the haptic version of the DMTS task. The stimuli and experimental paradigm were identical to experiment 1.

*Experimental Procedure*
In experiment 1, the sighted participants first performed the haptic version of the task to prevent them from using a memory representation of the visual stimuli during the haptic task. Detailed instructions about the task were followed by a training session without concurrent fMRI recording to eliminate learning and habituation effects. The training session was identical to the subsequent experimental session, except for the fact that subjects were given feedback about their performance. Importantly, subjects were never allowed to see any of the models, both during training and during experimental sessions. Haptic stimuli were placed on a tray on the right thighs of the subjects by the experimenter, so that they could reach them easily with their right hand, without extensive arm movement. Subjects were instructed to move their arm as little as possible, instead relying on hand movements to explore the stimuli. Button presses were always performed with the left hand. Following the haptic task, subjects performed the visual version and finally the functional localizer. In experiment 2, the blind subjects performed the haptic version of the DMTS task, using the same procedures for training and experimental sessions.

*Image Processing and Statistical Analysis of fMRI Data*
Image processing and statistical analysis were carried out using SPM8 (Wellcome Department of Imaging Neuroscience, London, UK). All volumes were realigned to the first volume, spatially normalized to an EPI template in a standard coordinate system [4] and finally smoothed using a 9 mm full-width at half-maximum isotropic Gaussian kernel. At the single-subject level, we applied a high pass filter (cut-off: 256s) to remove low frequency artifacts.
In experiment 1, we first created regions of interest (ROI) for the PPA in each of the sighted participants. To achieve this goal, we analyzed the data obtained from the functional localizer and specified design matrices with separate regressors for scenes and objects. Blocks of stimuli were modeled as boxcar functions convolved with a hemodynamic response function. We then identified the PPA as the cluster of contiguous voxels in the posterior part of the parahippocampal gyrus that showed stronger BOLD responses for scene than for object stimuli, using an uncorrected threshold of $p<.001$. Replicating previous findings [1, 3, 5], this approach proved successful since we were able to identify the PPA bilaterally in each sighted subject. For the subsequent analyses, we created both separate ROI's for the left and right PPA and a combined ROI by collapsing voxels from both hemispheres into one ROI.
Next, we estimated statistical models for the visual and the haptic DMTS task in the PPA-ROIs of each participant. We specified design matrices with separate regressors for scenes, objects and button presses, and blocks of stimuli were modeled as boxcar functions convolved with a hemodynamic response function. To account for potential confounds due to head motion, we also included six movement regressors (three translations and three rotations) as obtained from the realignment procedure. We then used the Marsbar toolbox to extract the mean time course across all voxels in the PPA-ROI, estimated the statistical model for the averaged time course, and entered the resulting parameter estimates for scene and object stimuli into a random effects paired t-test as implemented in the Matlab Statistics toolbox (version 7.4). Effect sizes were calculated by taking into account the correlation between both variables [6].
To look for regions outside the PPA showing differences between objects and scenes in the visual DMTS task, we performed a random effects whole-brain analysis. Specifically, the contrast images coding for the

main effects of both stimulus types were analyzed with a paired t-test as implemented in SPM8. Moreover, due to the relatively long block duration in the haptic condition, we estimated two models to test whether the PPA responses showed a habituation of the BOLD response over time. In the first model we tested for across block habituation by adding regressors in which the predicted hemodynamic responses for both conditions (scenes / objects) were parametrically modulated with the repetition of blocks (i.e. first object block, second object block etc.). In the second model, we modeled each stimulus as a separate event and added regressors that coded for the position of a stimulus within a block (within block habituation). For both models, the resulting parameter estimates for the parametric modulation regressors were then entered into random effects one-sample t-tests, but we did not observe any evidence for habituation effects (visual DMTS: within blocks – objects: $t=-0.05$, $p>0.5$; scenes: $t=1.54$, $p>0.1$; across blocks – objects: $t=0.05$, $p>0.5$; scenes: $t=0.70$, $p>0.5$; haptic DMTS: within blocks – objects: $t=-0.10$, $p>0.5$; scenes: $t=0.05$, $p>0.5$; across blocks – objects: $t=0.56$, $p>0.5$; scenes: $t=0.07$, $p>0.5$).

Because the match and sample stimuli differed with respect to the presence of furniture and toy characters (see Experimental Stimuli and Paradigm), we reran all analyses while only focusing on the sample stimuli and modeling the match stimuli as a separate regressor of no interest. These analyses replicated all the results reported in the main text; hence, the absence of the furniture and the toy characters in the match scenes did not seem to have a biasing effect.

Given the absence of a standard paradigm for localizing the PPA in blind people, we followed previously established procedures [7] and used the data from the functional localizer task of the sighted participants to define an average PPA ROI for experiment 2. Specifically, we performed a whole-brain fixed effects analysis in the sighted subjects and defined the PPA as the cluster of contiguous voxels in the posterior part of the parahippocampal gyrus that showed stronger BOLD responses for scenes than for objects. All subsequent analyses proceeded as for the sighted subjects.

As shown in table S3, our sample of blind participants was not completely homogeneous; hence factors such as age of onset of blindness or residual light perception could have had an unintended effect on our results. We believe this is unlikely given that each of the blind participants showed stronger activation for scenes than for objects, the fact that none had any more than light and minimal shape perception, and that the average duration of blindness was more than 37 years. Moreover, congenitally and adventitiously blind groups showed similar differences in PPA responses between scenes and objects (data not shown).

Finally, to test for overlapping and differential activations between blind and sighted subjects in the haptic delayed matching-to-sample task, we also performed a random effects whole-brain analysis across both groups. The contrast images coding for the main effects of both stimulus types in both subject groups were analyzed with a flexible factorial design as implemented in SPM8. To account for non-sphericity due to our repeated measures design, we explicitly modeled dependent error terms.

For each of the whole brain group analyses, correction for multiple comparisons (using a threshold of $p<.05$ corrected) was based on the entire brain and was performed using Gaussian Random Field Theory as implemented in SPM8. In contrast, note that the ROI analyses did not require correction for multiple comparisons as the subject specific statistical models were estimated for the mean time courses (averaged across all voxels in the respective ROI). As a consequence, for each participant, only one regression coefficient for scenes and one for objects entered the subsequent random effects models.

*Functional Connectivity Analysis*

How can we characterize potential mechanisms that could explain the scene sensitivity of the PPA in sighted subjects? Humans can extract the global structure of a visually presented scene as a combination of low-level filters of the type found in early visual areas, which is presumably read out by higher order areas. Given that the posterior parahippocampus receives direct projections from various occipital areas such as V2 and V4 [8, 9], we hypothesized that the stronger responses to scenes in the PPA might result from a stimulus-dependent modulation of the coupling strength between occipital cortex and the PPA. Moreover, we predicted similar effects in the haptic condition if subjects were engaging in visual mental imagery. We therefore performed two functional connectivity analyses with a functional connectivity toolbox (web.mit.edu/swg/software.htm) – one for the visual and one for the haptic condition – to identify

voxels in occipital cortex whose activation would exhibit a stronger covariation with the PPA during scene than during object blocks.

For each participant, we first removed several sources of confounding variance from the smoothed data through linear regression: estimated motion parameters, global average BOLD signal, average BOLD signals in ventricular and white matter ROIs and variance related to the main effects of the tasks. In addition, the data were high-pass filtered (cut-off: 256s) to eliminate low frequency drifts. Next, we extracted the mean time course across all voxels in the PPA as defined by the functional localizer and correlated it with all voxels in occipital regions V1, V2, V3, and V4 as defined by the SPM Anatomy toolbox [10]. Note that the PPA voxels from both hemispheres were combined as we did not observe hemispheric differences in the ROI analyses. We then tested for voxels in which this correlation was stronger during scene than during object blocks. Finally, the resulting contrast images were entered into a random effects paired t-test to assess differences between visual and haptic conditions. To take into account the anatomically motivated hypotheses, we applied multiple comparisons correction based on the four occipital regions of interest, again using Gaussian Random Field Theory.

## Supplemental References


1. Epstein, R., Harris, A., Stanley, D., and Kanwisher, N. (1999). The parahippocampal place area: Recognition, navigation, or encoding? Neuron *23*, 115-125
2. Epstein, R. (2005). The cortical basis of visual scene processing. Visual Cognition *12*, 954-978.
3. Epstein, R.A., Higgins, J.S., and Thompson-Schill, S.L. (2005). Learning places from views: Variation in scene processing as a function of experience and navigational ability. Journal of Cognitive Neuroscience *17*, 73-83.
4. Evans, A.C., Collins, D.L., Mills, D.R., Brown, E.D., Kelly, R.L., and Peters, T.M. (1993). 3D statistical neuroanatomical models from 305 MRI volumes. Proc. IEEE-Nuclear Science Symposium and Medical Imaging *1-3*, 1813-1817.
5. Epstein, R., and Kanwisher, N. (1998). A cortical representation of the local visual environment. Nature *39*, 598-601.
6. Dunlap, W.P., Cortina, J.M., Vaslow, J.B., and Burke, M.J. (1996). Meta-Analysis of Experiments With Matched Groups or Repeated Measures Designs. Psychological Methods *1*, 170-177.
7. Mahon, B.Z., Anzellotti, S., Schwarzbach, J., Zampini, M., and Caramazza, A. (2009). Category-specific organization in the human brain does not require visual experience. Neuron *63*, 397-405.
8. Gattas, R., Sousa, A.P., Mishkin, M., and Ungerleider, L.G. (1997). Cortical projections of area V2 in the macaque. Cerebral Cortex *7*, 110-129.
9. Ungerleider, L.G., Galkin, T.W., Desimone, R., and Gattass, R. (2008). Cortical connections of area V4 in the macaque. Cerebral Cortex *18*, 477-499.
10. Eickhoff, S.B., Stephan, K.E., Mohlberg, H., Grefkes, C., Fink, G.R., Amunts, K., and Zilles, K. (2005). A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. Neuroimage *25*, 1325-1335.