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Structural Differences in Hippocampal and Entorhinal Gray Matter Volume Support Individual Differences in First Person Navigational Ability

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Abstract—The ability to update position and orientation to reach a goal is crucial to spatial navigation and individuals vary considerably in this ability. The current structural MRI study used voxel-based morphometry (VBM) analysis to relate individual differences in human brain morphology to performance in an active navigation task that relied on updating position and orientation in a landmark-free environment. Goal-directed navigation took place from either a first person perspective, similar to a person walking through the landmark-free environment, or Survey perspective, a bird's eye view. Critically, the first person perspective required a transformation of spatial information from an allocentric into an egocentric reference frame for goal-directed navigation. Significant structural volume correlations in the hippocampus, entorhinal cortex, and thalamus were related to first person navigational accuracy. Our results support the theory that hippocampus, entorhinal cortex, and thalamus are key structures for updating position and orientation during ground-level navigation. Furthermore, the results suggest that morphological differences in these regions underlie individual navigational abilities, providing an important link between animal models of navigation and the variability in human navigation. **© 2018 IBRO. Published by Elsevier Ltd. All rights reserved.**

Key words: thalamus, VBM, MRI, structural, human, navigation.

INTRODUCTION

The ability to successfully navigate in the world varies dramatically across individuals, yet "navigational ability" may not be a singular capacity (Wolbers and Hegarty, 2010; Chrastil, 2013). A number of navigational strategies rely on the use of landmarks, which can be used to anchor specific spatial locations or goals. Navigational abilities in landmark-rich environments have been shown to rely on differences in underlying brain structure (Bohbot et al., 2007; Woollett and Maguire, 2011; Hartley and Harlow, 2012; Brown et al., 2014a). Humans can also navigate successfully in landmark-free environments (Wolbers et al., 2007; Sherrill et al., 2013; Chrastil et al., 2015), and this study examined individual differences in the ability to navigate in landmark-free environments. A vital ability to navigate in landmark-free environments is the capability to update position and orientation to reach a goal, which we tested during successful navigation toward an encoded goal location. The goal of the present study was to test how variation in navigational ability within this environment relates to underlying neuroanatomical structure in the healthy human brain.

By using self-motion cues to accurately guide one's position in an environment, more precise navigation to an intended goal is possible. Recent functional MRI studies have demonstrated that the hippocampus supports goal-directed navigation (Hartley et al., 2003; Zhang and Ekstrom, 2013; Brown et al., 2014b). Previous studies have linked hippocampal volumetric differences to topographical and spatial abilities during landmark-based navigation (Bohbot et al., 2007; Schinazi et al., 2013; Brown et al., 2014b; Guderian et al., 2015). A recent study has provided the first evidence of gray matter volume differences, including the hippocampus, are related to path integration abilities (Chrastil et al., 2017). However, the link between hippocampal gray matter volume and navigational ability has not yet been established when updating position and direction are essential during goal-directed navigation.

Animal models suggest that the entorhinal cortex and thalamus, in addition to the hippocampus, support goal-directed navigation (see Hasselmo and Stern, 2015, for review). In rodents, specialized head direction cells fire

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Abbreviations: AAL, automated anatomical labeling; CSF, cerebral spinal fluid; ERC, entorhinal cortex; FPP, first person perspective; ITI, inter-trial interval; ROI, region of interest; TPP, third person perspective; VBM, voxel-based morphometry.

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as a function of the animal's current heading, independent of location. Head direction cells are modulated by self-motion cues (Taube, 2007) and are found within the thalamus (Taube, 1995). These cells complement place cells in the hippocampus and grid cells in the entorhinal cortex, which are spatially tuned to represent specific locations in the environment and code arrays of locations via a triangular coordinate system, respectively (O'Keefe and Dostrovsky, 1971; Hafting et al., 2005). Positional and directional information may be integrated within the rodent navigational network in the medial temporal lobe by neurons with conjunctive place and directional properties (Sargolini et al., 2006). Studies of human navigation have started to establish that these same spatially tuned regions are present in the human and are activated when coding location (Ekstrom et al., 2003), arrays of locations (Doeller et al., 2010; Jacobs et al., 2013), and heading direction (Shine et al., 2016). However, correlates of navigational ability and human brain structure within the hippocampus, entorhinal cortex, and thalamus have not been established.

Taken together, functional and structural data from previous studies led to the prediction that greater gray matter volumes in the hippocampus, entorhinal cortex, and thalamus will provide a more robust architecture for updating position and orientation during goal-directed navigation. We tested this prediction by relating gray matter volume estimates in healthy young adults to individual differences in performance during a navigation task, in which updating position and orientation would be integral to success. In our navigation task, participants viewed a map of a landmark-free environment indicating the start and goal locations, then transformed these survey-level spatial representations to actively navigate the environment in either the first person perspective (FPP) or Survey (Bird's eye) perspectives (Sherrill et al., 2013). For first person perspective goal-directed navigation, which requires updates of position and orientation after changing from an allocentric to an egocentric perspective, we predicted that humans with better accuracy during navigation requiring position and orientation updates would have greater gray matter volume in the hippocampus, entorhinal cortex, and thalamus compared to those with poorer navigational performance.

EXPERIMENTAL PROCEDURES

Participants

Fifty-seven participants (27 females, mean age 22.35 ± 3.60 years (SD)) from the Boston University student community were included in the analysis. Participants had no history of neurological or psychiatric disorders. Written informed consent was obtained from each participant prior to enrollment in accordance with the experimental protocol approved by both the Partners Human Research Committee and the Boston University Institutional Review Board.

Virtual navigation environment

Detailed information about the navigation paradigm can be found in our earlier fMRI publication (Sherrill et al., 2013). Briefly, participants were shown a survey representation of their start location, heading direction, and a goal location. Following a delay, the participants actively navigated to the encoded goal location using a button box. Panda3D Software (Entertainment Technology Center, Carnegie Mellon University, PA) was used to create the virtual environment consisting of an open field, with no distal landmarks or distinguishing proximal landmarks (Fig. 1). One virtual unit represented 0.5 meters in the virtual environment. Short, circular columns (radius six virtual units, height 0.15 virtual units) were placed upon the floor of the open field to prevent participants from moving directly to the goal location. Thus, navigational routes arced around the columns, encouraging active computation and maintenance of orientation.

Navigation occurred from either the first person perspective (FPP), or a Survey perspective (Fig. 1). In both perspectives, movement speed was held constant at five virtual units per second. In the FPP, the participant's perspective was set at a height of two virtual units. The field of view during FPP navigation was restricted to the scene in front of the participant, consistent with the definition of first person perspective. In the Survey perspective, the participant steered a vehicle to the goal location from a fixed, survey-level perspective looking directly down at the center of the environment (Fig. 1). Further description of the virtual environment can be found in Sherrill et al. (2013). In the current experiment, participants completed one of two navigational paradigms within the same virtual environment. The navigational tasks are described below in Experimental tasks.

Training procedures

Both experiments included in the current analysis were conducted over two consecutive days. One day prior to scanning, participants were trained on the navigation task. In the task, they encoded start and goal locations from a survey-level map perspective then translated this spatial representation into accurate, goal-directed navigation (Sherrill et al., 2013; Sherrill et al., *in preparation*). Scanning data were collected the day after initial training. Participants were given a practice run to refamiliarize themselves with the task and keyboard controls once placed in the scanner.

Experimental tasks

Data included in the present morphometric analysis were collected using the same scanning protocol and scanner, but across two navigational fMRI paradigms (Sherrill et al., 2013; Sherrill et al., *in preparation*). Both tasks had navigational conditions in which the participant navigated in either the FPP or Survey perspective with no distinguishing landmarks, distal cues, or goal location markers present in the environment. These conditions

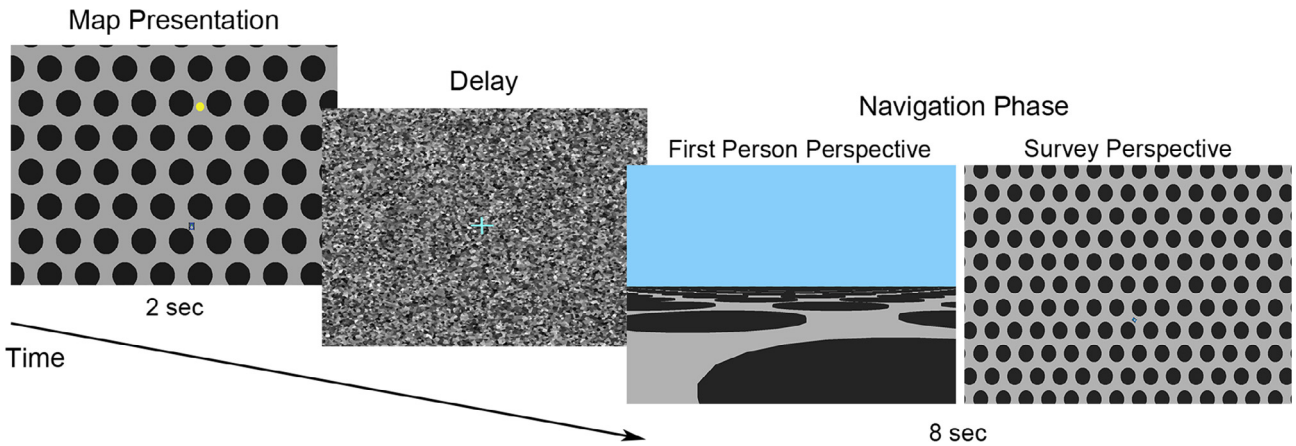

Fig. 1. Task paradigm. During the two-second map presentation, participants were shown a survey representation of the environment indicating their start location, orientation, and goal location. Following a delay was an eight-second navigation phase requiring active navigation to the goal location in which movement occurred from either the first person perspective (FPP) or a Survey perspective.

were consistent across the two paradigms and behavioral data from these trials were combined for this study. The two navigational paradigms are described below.

In both tasks, each trial consisted of map presentation, delay, and navigation phases, followed by an inter-trial interval (ITI). During the two-second map presentation, participants were shown a survey representation of the environment with their start location, orientation, and goal location clearly marked. Following a delay, was an eight second navigation phase that required active navigation to the goal location. Participants were instructed to navigate to the precise location where they thought the encoded goal was located. The goal location was not visible during the navigation phase, and no feedback was given as to whether the participant successfully reached the goal location. A trial was considered correct if participants' trajectories during the navigation phase came within a radius of three virtual units from the goal location. Critically, no distinguishing landmarks, distal cues, or goal location markers were present in the environment. This sparse environment required participants to merge self-motion cues from optic flow with their planned route during ground-level navigation. There were forty trials per experimental condition. The minor differences between the two navigation tasks are as follows:

Navigation Task 1: Goal-directed navigation with no distinguishing landmarks. In Task 1 (Sherrill et al., 2013), trials of the FPP and Survey perspective were presented along with a third condition, third person perspective (TPP). The three conditions were presented in an interleaved, randomized order. Trials in which navigation occurred from the TPP were not included in the current analysis. Participants did not know trial type (FPP, TPP, or Survey perspective navigation) until the start of the navigation phase. The order of the trials was counterbalanced across runs, and the order of runs was randomized across participants. During functional scanning, participants performed ten runs composed of twelve trials per run.

Navigation Task 2: Goal-directed navigation with or without the presence of an orienting landmark. In the second navigational task, we modified the original paradigm (Sherrill et al., 2013) to include a landmark condition (Sherrill et al., *in preparation*). This modification allowed us to examine successful navigation with or without an orienting landmark present in the environment. Half of the trials were the same as the FPP and Survey perspective conditions in Navigation Task 1, and these trials are included in the analysis here. On the other half of the trials, a landmark—a single column colored blue—was present in the environment. The landmark was visible in both map presentation and navigation phases. Trials containing FPP or Survey perspective navigation phases with or without a landmark were presented in an interleaved, randomized order. Participants did not know the trial type (FPP or Survey perspective) until the start of the navigation phase. The order of the trials was counterbalanced across runs, and the order of runs was randomized across participants. During functional scanning, participants performed ten runs composed of sixteen trials per run. We emphasize that the trials with the orienting landmark were not included in the present analysis.

In summary, the differences between the two navigational tasks were minimal with regard to the conditions analyzed. Navigation task 1 had an additional experimental condition (Third person perspective, TPP), and Navigation task 2 had an additional navigational condition (landmarks). These conditions were presented in separate trials, and behavior from these trials is not included here. The delay was ten seconds in Navigation task 1 and four seconds in Navigation task 2, which also used a white-noise mask during the delay.

MRI image acquisition

Images were acquired at the Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital in Charlestown, MA using a 3 Tesla Siemens MAGNETOM TrioTim scanner with a 32-channel Tim Matrix head coil. High-resolution T_1-weighted multiplanar rapidly acquired gradient echo (MP-RAGE)

structural scans were acquired using Generalized Autocalibrating Partially Parallel Acquisitions (GRAPPA) (TR = 2530 ms; TE = 3.31 ms; flip angle = 7°; slices = 176; resolution = 1 mm isotropic).

Voxel-based morphometry

Gray matter volume was analyzed using standard voxel-based morphometry (VBM) methods in SPM8 (Wellcome Department of Cognitive Neurology, London, UK). Structural images were segmented using SPM8's New Segment option into gray matter, white matter, and cerebral spinal fluid (CSF) images, and bias-corrected. Gray matter segmentation images were spatially normalized into standard Montreal Neurological Institute space using the Diffeomorphic Anatomical Registration Through Exponentiated Lie algebra (DARTEL) algorithm (Ashburner, 2007) for a high degree of intersubject registration. Gray matter images were resampled during normalization (1.5 mm^3 isotropic voxels) and spatially smoothed using a 6 mm full-width at half-maximum Gaussian kernel. VBM analyses were conducted using standard "modulated" smoothed gray matter images, providing a measure of regional gray matter volume (Mechelli et al., 2005).

Behavioral analyses

Behavioral performance. To compare overall performance between the FPP and Survey perspective experimental conditions, a paired-samples t-test was run comparing accuracy in the two conditions. Individual trials were considered correct if participants' trajectories during the navigation phase came within a radius of three virtual units from the goal location. A Pearson's correlation was also conducted to assess the relationship of accuracy between the FPP and Survey perspective experimental conditions (Fig. 2). Behavioral analyses were completed using PASW Statistics 18 (SPSS, Inc., Chicago, IL).

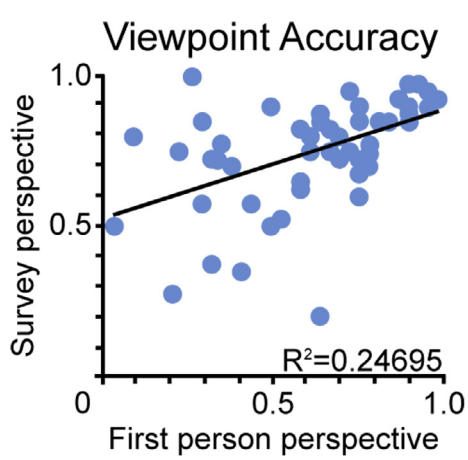

Fig. 2. Individual differences in navigational accuracy across experimental conditions. The scatter plot assesses the relationship between accuracy in the FPP and Survey perspective experimental conditions. Each dot represents an individual participant's proportion correct from the FPP and Survey perspective navigation conditions.

VBM statistical analysis

Individual subject performance on the two experimental conditions (FPP and Survey perspective navigation) were entered as covariates with smoothed gray matter volume estimate images into a second-level multiple regression analysis in SPM8. *T* statistic images, representing the strength of the linear association, were calculated in SPM. Significant positive relationships indicated local gray matter volume estimates were predicted by accuracy in the condition of interest. Individual subject ages, sex, study, and total brain volume were included as additional covariates for the regression analysis to control for their potentially confounding influence on brain structure and performance.

Region of interest (ROI) and whole-brain volumetric analyses were performed for FPP and Survey perspective navigation phases. Prior human and animal literature informed our *a priori* hypotheses that the hippocampus contributes to navigation in sparse environments (Sherrill et al., 2013; Chrastil et al., 2015, 2016; O'Keefe and Dostrovsky, 1971; Pfeiffer and Foster, 2013), that the thalamus contributes to heading direction during movement (Taube, 1995, 1998; Jankowski et al., 2013; Shine et al., 2016), and that the entorhinal cortex contributes to navigational coding (Hafting et al., 2005; McNaughton et al., 2006; Brun et al., 2008). Based on our strong anatomical predictions and to limit the multiple-comparisons problem, regression analyses were conducted within a restricted ROI volume comprised of the hippocampus, thalamus, and parahippocampal cortex (14,361 voxels). Our search volume was created by combining relevant automated anatomical labeling (AAL) structural delineations (Tzourio-Mazoyer et al., 2002) from the Wake Forest University (WFU) PickAtlas for SPM (Maldjian et al., 2003, 2004). We included the parahippocampal cortex AAL structural delineation in our ROI because it contains the entorhinal cortex. Activation within the entorhinal cortex was delineated using anatomical demarcations from Insausti et al. (1998) and Pruessner et al. (2002). Analyses in the ROI were conducted with voxelwise statistical thresholds of $p < 0.05$. To limit the occurrence of spurious clusters, we applied a cluster-extent threshold (k) of 180 to maintain a family-wise error rate of $p < 0.01$, calculated using a 10,000 simulation Monte Carlo analysis in 3dClustSim (for the AFNI software package – http://afni.nimh.nih.gov/afni/; AFNI version 16.0.01 (2016)). For visualization purposes, gray matter volumes were extracted from 5-mm spheres centered on peak coordinates in regions of interest and plotted against proportion correct in the FPP navigation condition (Fig. 3).

Whole-brain analyses were conducted with voxel-wise statistical thresholds of $p < 0.05$. To limit the occurrence of spurious clusters, we applied a cluster-extent threshold (k) of 946 to maintain a family-wise error rate of $p < 0.05$. The cluster-extent was calculated using a 10,000 iteration, 6-mm autocorrelation Monte Carlo simulation

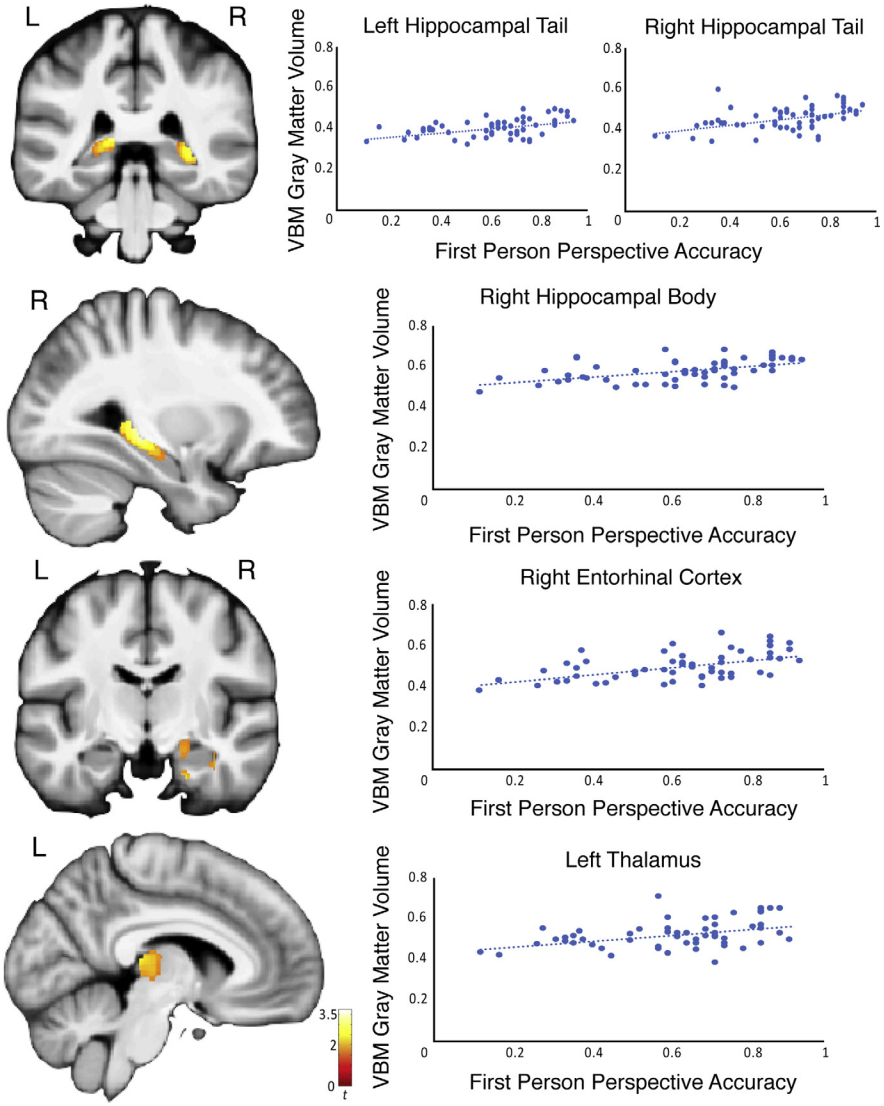

Fig. 3. Gray matter volumes within our ROI correlated with successful first person perspective (FPP) goal-directed navigation. Scatter plots indicate the distribution of individual gray matter volume estimates around the regression line based on the full model. All *t*-values exceed a threshold equivalent to a voxel-wise *p*-value of 0.05, cluster corrected to 0.01 (min cluster size 180).

analysis on voxels within the group functional brain space using the ResMS header file (339,494 voxels). Significant brain regions at the whole-brain level are reported in Table 1.

RESULTS

Behavioral results

We examined navigation performance to determine differences in accuracy when navigating from FPP and Survey perspectives across all participants. A trial was considered correct if participants' trajectories during the navigation phase came within a radius of three virtual units from the goal location. Due to the small radius size and infinite environment structure, participants had a low probability of navigating to the goal based on chance. Navigation to the goal relied on updating position and orientation within the landmark-free environment. Participants reached the goal location with precision from the first person perspective (FPP) in 64.04% of the trials (SEM 2.73) and from the Survey perspective (Survey) in 75.39% of the trials (SEM 2.32). A significant difference in percent correct was found using a paired sample *t*-test between accuracy from the FPP and Survey conditions during the navigation phase ($p = 0.001$; $t = 4.477$).

We examined the distribution of navigational accuracy across experimental conditions (FPP and Survey perspective navigation). A scatter plot displays the significant relationship of navigational accuracy between the FPP and Survey perspective experimental conditions ($R^2 = 0.24695$, $p < 0.001$) (Fig. 2).

Voxel-based morphometry (VBM) results

First person perspective navigation. A significant positive relationship between structural morphology and navigational accuracy from the FPP was found within our ROI, specifically in bilateral hippocampus tail and body, right entorhinal cortex, and bilateral thalamus (Fig. 3). A significant positive relationship was also present at the whole-brain level within the hippocampus, entorhinal cortex, and thalamus (Table 1). One cluster in our ROI ($k = 744$) spanned left hippocampus tail and bilateral thalamus. Another cluster ($k = 342$) spanned the left hippocampus body, and a separate cluster ($k = 887$) spanned right hippocampus head, body, and tail and right entorhinal cortex. These results indicate that participants who more successfully updated position and orientation during FPP goal-directed navigation have greater gray matter volume in these navigationally responsive brain regions. Peak voxel location, cluster size (k), and *t*-value and *p*-value for the peak voxels are as follows: hippocampal tail (x, y, z: −18, −40,4: $t_{(56)} = 2.48$; $p < 0.01$; $k = 744$; x, y, z: 32, −33, −5: $t_{(56)} = 3.24$; $p < 0.01$; $k = 887$), hippocampal body (x, y, z: −30, −21, −14: $t_{(56)} = 2.62$; $p < 0.01$; $k = 342$; x, y, z: 31.5, −25.5, −12: $t_{(56)} = 3.47$; $p < 0.01$; $k = 887$), entorhinal cortex (x, y, z: 21, −12, −31.5: $t_{(56)} = 2.40$; $p < 0.01$; $k = 887$), and thalamus (x, y, z: −10, −18, 10: $t_{(56)} = 2.19$; $p < 0.01$; $k = 744$; x, y, z: 4.5, −21, 7.5: $t_{(56)} = 1.71$; $p < 0.01$; $k = 744$). Our

Table 1. Whole-brain voxel-based morphometry results for first person perspective (FPP) and Survey navigation conditions. All *t*-values exceed a threshold equivalent to a voxel-wise *p*-value of 0.05, cluster corrected to 0.05 (min cluster size 946)

		K_E	Left		K_E	Right	
Condition	Area		T	MNI *x*, *y*, *z*		T	MNI *x*, *y*, *z*
First person	Hippocampus (Tail)	946	2.48	−18, −40, 4	1482	3.30	30, −33, 1
	Hippocampus (Body)					3.47	31.5, −25.5, −12
	Hippocampus (Head)					2.02	21, −15, −22.5
	Entorhinal cortex					2.48	19.5, −12, −33
	Thalamus	946	2.19	−10, −18, 10	946	1.71	4.5, −21, 7.5
	Insula				1931	2.53	41, −12, −3
	Dorsal lateral prefrontal cortex				1207	3.00	46.5, 31.5, 36
	Inferior frontal gyrus					2.84	53, 9, 1
	Temporal pole				1931	4.31	32, 10, −35
Survey	Angular gyrus				1101	3.10	28, −70, 36
	Cuneus					2.86	15, −91, 33
	Postcentral gyrus	2285	3.01	−30, −34, 67	1146	2.89	42, −13, 63
	Paracentral gyrus		3.22	−4, −33, 66			
	Cingulate gyrus		2.93	−6, −10, 43			
	Precentral gyrus	1653	2.49	−49.5, −7.5, 51			

whole-brain analysis also found that these regions related to FPP goal-directed navigation (Table 1). Additionally, a positive relationship between navigational accuracy from the first person perspective and the left entorhinal cortex (x, y, z: −21, −10, −34; $t_{(56)} = 2.64$; $p < 0.05$; $k = 53$) was found at the whole-brain level using an exploratory cluster extent of 50. These significant volumetric differences and exploratory results support the hypothesis that bilateral hippocampus, entorhinal cortex, and thalamus are important for updating position and orientation during navigation.

Survey perspective navigation. There was no significant relationship with navigational accuracy from the Survey perspective within our ROI. At the whole-brain level, gray matter volume in right angular gyrus (x, y, z: 28, −70, 36: $t_{(56)} = 3.10$; $p < 0.05$; $k = 1101$) and primary motor regions (x, y, z: −30, −34, 67: $t_{(56)} = 3.01$; $p < 0.05$; $k = 2285$; x, y, z: 42, −13, 63: $t_{(56)} = 2.89$; $p < 0.05$; $k = 1146$) had a significant positive relationship with navigational accuracy from the Survey perspective. Greater volumetric differences in these rotational and motor brain regions correlated with people who more successfully reached the goal location during Survey perspective navigation (Table 1).

DISCUSSION

Human navigation is complex and highly variable. A key contributor to individual differences in navigational abilities may be variations in fundamental processes, such as updating position and orientation, that are essential to our navigational success. Our results provide evidence that entorhinal and thalamic gray matter volume relates to performance during successful goal-directed navigation in an environment that requires updating position and orientation in healthy young adults. In particular, navigation from the first person perspective required transforming the spatial viewpoint from an allocentric, top-down perspective into an egocentric perspective, all while updating position and orientation with respect to the goal. In addition, results from the current study support previous work indicating that individual differences in navigational performance correlate with hippocampal structure. Together, these findings support the theory that morphological differences in hippocampus, entorhinal cortex, and thalamus gray matter volume underlie individual navigational abilities, providing an important link between animal models of navigation and human variability.

Structural morphology correlates with entorhinal gray matter volume during FPP goal-directed navigation

Current understanding of the role of entorhinal cortex in human navigation has been built by connecting varying levels of neuroscientific investigation, from membrane potentials to individual neurons, from neuronal networks to complex behavior. Grid cells within the rodent medial entorhinal cortex increase their firing rates to code arrays of locations via a triangular coordinate system (Hafting et al., 2005). Studies of human navigation have established that these same spatially-tuned cells are present in the human, suggesting a similar spatial system may support goal-directed navigation in humans (Doeller et al., 2010; Jacobs et al., 2013). Results from the current study highlight the importance of entorhinal cortex by demonstrating that participants who were more accurate in navigating to the goal location from the first person perspective (FPP) had larger entorhinal cortex volumes. Greater gray matter volume in the entorhinal cortex could provide greater neural resources for updating position and orientation from spatially-tuned cells within the cortex.

Consistent with its role in spatial coding, gray matter volume in the entorhinal cortex had a significant relationship with performance during goal-directed navigation from the first person perspective (FPP). In the current study, gray matter volume differences in the entorhinal cortex were present in the posterior region of the entorhinal cortex. Anatomically, the posterior

entorhinal cortex is the human homolog to the rodent medial entorhinal cortex (Witter et al., 2000; van Strien et al., 2009; Navarro Schröder et al., 2015; Maass et al., 2015; Burgess, 2008; Jacobs et al., 2010). The location of our structural differences suggests that gray matter variances found in this study are in the homologous position to the rodent medial entorhinal cortex. Our results demonstrate that greater entorhinal volumes support successful navigation in the absence of landmarks, where there is a reliance on updates of orientation and position.

Gray matter volume in the thalamus and successful FPP goal-directed navigation

The thalamus is a large and very heterogeneous structure. Our data were collected from a single ROI that included the entire thalamus, which does not allow us to relate the volumetric changes in the thalamus as a whole to a particular behavioral feature. The volumetric differences found in our study were localized primarily in the posterior thalamus and midline nuclei. Midline nuclei including the nucleus reuniens have a reciprocal connection with the medial prefrontal cortex and terminal fields in the hippocampus; this circuit is critical for goal-directed navigation (Ito et al., 2015). The posterior thalamus has projections to the superficial layers of the posterior parietal cortex (Avendaño et al., 1990). Animal models demonstrate that the posterior parietal cortex supports representations of space for movements within an egocentric coordinate frame (Sato et al., 2006; Save and Poucet, 2009; Whitlock et al., 2012).

Human neuroimaging data from Spiers and Maguire (2006) demonstrated that the posterior parietal cortex was recruited during active navigation to a goal, suggesting a role in the coding and monitoring of response-based spatial information concerning distant locations. Additionally, a recent human neuroimaging study found that the posterior thalamus integrates both visual and body-based orientation cues during navigation (Shine et al., 2016). In the current task, navigation within the first person perspective requires transforming the spatial viewpoint from an allocentric, top-down perspective into an egocentric, or body-based, perspective. Our results provide novel evidence that there is a significant positive relationship between thalamic gray matter volume and accuracy in a FPP navigation task in which orientation updates are key to success. Greater structural morphology in the thalamus may be indicative of larger orientation signals, which increase navigational accuracy when navigation is dependent upon updating your orientation signal during movement.

Hippocampal gray matter volume and successful FPP goal-directed navigation

Our finding that navigational accuracy has a positive relationship with gray matter volume in the hippocampus is consistent with evidence that the hippocampus supports goal-directed navigation. Place cells in the hippocampus provide spatial tuning through structured responses that code position in an environment (O'Keefe and Dostrovsky, 1971; Ekstrom et al., 2003; Hassabis et al., 2009; Brown et al., 2016). Previous research has linked hippocampal volume with individual differences in navigational ability in landmark-based navigation (Woollett and Maguire, 2011; Hartley and Harlow, 2012; Brown et al., 2014b; Wegman et al., 2014). Additionally, increased navigation within a landmark-based environment, i.e. London taxi drivers, correlated with increased posterior hippocampal volume, indicating a causal relationship between navigational skill and local plasticity (Maguire et al., 2000, 2006). Our previous functional neuroimaging study found that utilizing self-motion cues to update position and orientation during successful FPP navigation recruits the hippocampus (Sherrill et al., 2013). Results from the present study support a structural–functional relationship depending on the reference frame, with navigationally responsive regions correlating more with egocentric, first person navigational abilities than with Survey navigation. Larger gray matter volume in the hippocampus could provide greater neural resources to support hippocampal position computations, corresponding with higher performance during FPP goal-directed navigation.

Several neuroimaging studies have also shown a relationship between hippocampal activity and distance to a goal location (Spiers and Maguire, 2007; Morgan et al., 2011; Sherrill et al., 2013; Howard et al., 2014; Chrastil et al., 2015). We demonstrated that the posterior hippocampus plays a role in coding proximity to a goal location during active navigation (Sherrill et al., 2013). Results from our volumetric analysis supplement this finding, suggesting that navigators with larger hippocampal tail gray matter volume may have greater neural resources to track distance toward a goal location, increasing their behavioral performance on the task.

Gray matter correlates during Survey perspective navigation

Volume-based morphometry results from this study demonstrate that there is a positive relationship between volume in the angular gyrus and accuracy during Survey perspective navigation. In the Survey perspective navigation condition, participants had to mentally rotate themselves to their start orientation in order to accurately navigate the vehicle, particularly when starting from a south facing location (a complete 180 degree mental rotation). Angular gyrus activation has been associated with mental rotation (Keehner et al., 2006; Schendan and Stern, 2007), displacement estimation (Diekmann et al., 2009), and mental navigation in a familiar environment (Rosenbaum et al., 2004). One possibility is that the angular gyrus may improve navigation from a Survey perspective when mental rotation is key to reaching an encoded goal location.

CONCLUSIONS

Using voxel-based morphometry (VBM), we provide novel evidence that accuracy during goal-directed navigation—which requires updates in position and orientation—relates to gray matter volume estimates in the entorhinal

cortex, thalamus, and hippocampus of healthy, young adults. These results were specific to navigation from the first person perspective, further supporting functional data that resources within these regions are recruited to update position and orientation calculations during navigation. Results from this study suggest that individual differences in hippocampal, entorhinal, and thalamic anatomy may provide a neuroanatomical substrate for individual differences in utilizing position and orientation mechanisms during navigation.

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