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Research Report

Neural representation of object location and route direction: An event-related fMRI study

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ABSTRACT

The human brain distinguishes between landmarks placed at navigationally relevant and irrelevant locations. However, to provide a successful wayfinding mechanism not only landmarks but also the routes between them need to be stored. We examined the neural representation of a memory for route direction and a memory for relevant landmarks. Healthy human adults viewed objects along a route through a virtual maze. Event-related functional magnetic resonance imaging (fMRI) data were acquired during a subsequent subliminal priming recognition task. Prime-objects either preceded or succeeded a target-object on a preciously learned route. Our results provide evidence that the parahippocampal gyri distinguish between relevant and irrelevant landmarks whereas the inferior parietal gyrus, the anterior cingulate gyrus as well as the right caudate nucleus are involved in the coding of route direction. These data show that separated memory systems store different spatial information. A memory for navigationally relevant object information and a memory for route direction exist.

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1. Introduction

To successfully find our way through familiar and unfamiliar environments, we have to know where we are and where we have to go from there to reach a goal. To this end, memory for relevant object location and for route direction is needed, and both have to exchange information. This study focuses on how the human brain represents different spatial information and enables us to successfully find our way. Neuroimaging studies have shown the involvement of the mediotemporal lobe (for an overview on medial temporal lobe activity see Henson, 2005), including the hippocampus and the parahippocampal gyrus, as well as the parietal lobe in spatial memory and navigation (e.g., Burgess et al., 1999; Maguire et al., 1998; Shelton and Gabrieli, 2002; Voermans et al., 2004). Whereas the mediotem-

poral lobe is known to represent objects and their spatial locations in an allocentric frame of reference making use of world-centred coordinates, the parietal lobe is involved in representing spatial information in an egocentric reference frame making use of the viewer's bodily coordinates (Burgess et al., 1999; O'Keefe and Nadel, 1978; Wolbers et al., 2004). These results suggest distinct memory systems storing different spatial information.

Previous behavioral studies have shown that the direction in which a route is traveled is part of the spatial representation. This effect of route direction (Herrmann et al., 1995; Janzen, 2006; Schweizer et al., 1998) was observed using a spatial priming paradigm (McNamara et al., 1984; McNamara, 1992). Participants performed an object recognition task and responded to target-objects that were primed in or against the

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direction of a previously traveled route. Behavioral results showed a response time advantage for in-route items as compared to against-route items that were taken as evidence that route direction is part of the acquired spatial representation. So far, the brain areas involved in coding of route direction are unknown.

Not only routes between different locations need to be memorized but also the locations themselves. Recent fMRI studies by Janzen and van Turennout (2004; Janzen et al., 2007) have shown that activity in the parahippocampal gyrus is increased for objects previously placed at decision points as compared to objects at locations with less navigational relevance, i.e. at non-decision points. This increased activation for decision-point objects was observed even when participants could not remember that they had seen the object before. These results suggest selective representation of navigationally relevant information in the parahippocampal gyrus.

The previous behavioral and neuroimaging results suggest the existence of two distinct memory systems: a memory for route direction and a memory for relevant object location. To successfully guide our way through our spatial surroundings, both memory systems need to exchange information. The present fMRI study investigates the neural correlates of a representation of route direction, a representation of navigationally relevant object information and a possible interaction of both representations.

In a study phase, participants watched a film sequence through a virtual maze outside the scanner with objects placed at decision and at non-decision points (Fig. 1A). Afterwards, fMRI time series were obtained while participants performed an object recognition task. A subliminal spatial priming paradigm was used showing two objects, a prime-object followed by a target-object. Both objects had been at a given spatial location in the previously seen maze. Participants responded only to the target-object and indicated whether they had seen the target-object in the maze. To investigate memory for route direction, prime and target had followed each other in the traveled direction along the route (in-route items) or against the traveling direction (against-route items). To investigate memory for object location, prime- and target-objects were placed either at decision points (decision-point items) or at non decision points (non-decision-point items). All items were shown randomly intermixed. In order to rule out an influence of strategies a subliminal priming paradigm was used, i.e. the prime-object was masked and therefore not consciously available (Fig. 1B). For a recent discussion on masked (or unconscious) priming processes, see for example Dehaene et al. (2006), Kiefer (2002), Naccache and Dehaene (2001), and Vorberg et al. (2003).

Based on previous results (Janzen and van Turennout, 2004; Janzen et al., 2007), we predicted increased neural activity in bilateral parahippocampal gyrus for decision as compared to

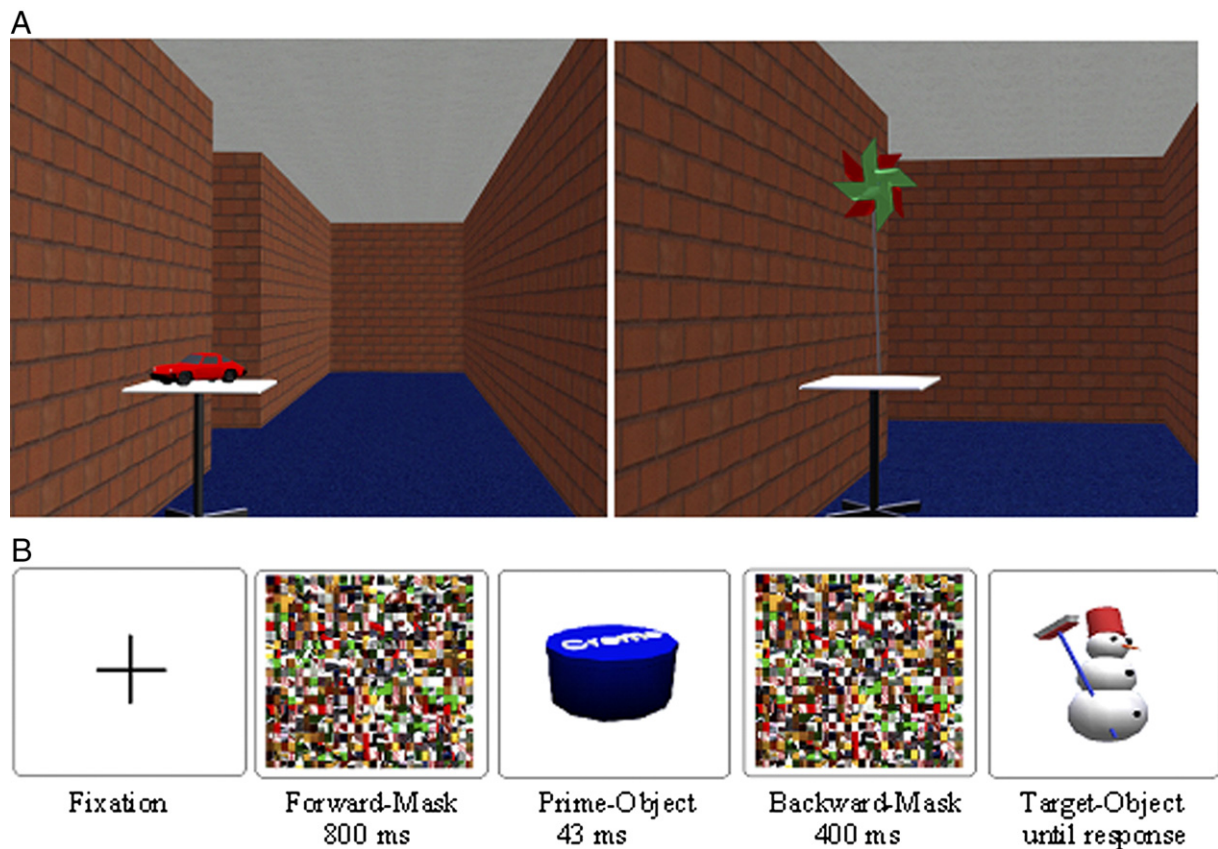


Fig. 1 – Virtual environment and priming task. (A) Two scenes out of the virtual environment that participants viewed in the study phase. The red car was placed at a decision point and the windmill was placed at a non-decision point. **(B)** Subliminal priming task in the recognition phase. Participants decided whether or not they had seen the target object during the study phase.

non-decision-point items. Recent data show that the parietal lobe is associated with spatial representations in an egocentric reference frame (Burgess et al., 1999; Cohen and Andersen, 2002). The representation of the traveling direction makes use of the body coordinates with the clear front and back of the traveling person and is therefore likely to be represented in an egocentric frame of reference. Based on these considerations, we expected increased neural activity in the parietal lobe for in-route as compared to against-route items.

2. Results

2.1. Behavioral results

Task performance was above chance level (see Table 1). Recognition accuracy was calculated as the difference in probabilities of correct decisions for objects included in the mazes (hits) and incorrect decision for distractor items (false alarms). ($Pr = \text{probability hits} - \text{probability false alarms}$). Because of the low number of false alarms, the overall recognition performance greatly exceeded chance level ($Pr = 0.44 \pm 0.16$; $t(14) = 10.51$; $p < 0.001$). No differences in error rates among the experimental conditions (D-objects in-route: $38.5\% \pm 19.3\%$; D-objects against-route: $42\% \pm 15.6\%$; ND-objects in-route: $41.9\% \pm 16.9\%$; ND-objects against-route: $37.9\% \pm 16.5\%$) were observed.

An ANOVA of the response times (RT) with the factors decision-point and route directions showed no main effects and no interaction. Mean response times and standard error (SE) for D-objects in-route were 927.04 ms (SE=31.18 ms), for D-objects against-route 921.38 ms (SE=37.17 ms), for ND-objects in-route (937.73 ms (SE=34.14 ms), and for ND-objects against-route 922.92 ms (SE=35.08). Two behavioral pre-tests using the same maze and priming task demonstrated faster response times for decision-point items than for non-decision-point items, and faster response times for in-route items as compared to against-route items. These results are described in the Supplementary data.

2.2. Functional imaging data

Objects from the mazes as compared to a low level visual baseline (scrambled objects) activated bilateral occipitotemporal cortices known as the ventral visual pathway (Ungerleider and Mishkin, 1982). Increased activity was additionally found bilaterally in the hippocampus, the parahippocampal gyrus, posterior cingulate gyrus, and the left superior parietal lobe.

To investigate effects of navigational relevance of object location, we compared fMRI responses to decision-point items

with responses to non-decision-point items. This comparison revealed increased activity for decision-point items in the parahippocampal gyrus and the hippocampus bilaterally (Fig. 2). To investigate the effect in the temporal lobe in more detail, a region of interest analysis was performed on all voxels showing a decision-point effect (see Experimental procedures). An ANOVA of the regionally averaged beta-weights was performed separately for the right and left parahippocampal gyri and the hippocampus. As expected from the fMRI comparison, a main effect of decision point (decision vs. non-decision points) in the parahippocampal gyrus (left parahippocampal gyrus: $F(1,14) = 7.69$, $P < 0.01$; right parahippocampal gyrus marginally: $F(1,14) = 4.13$, $P = 0.06$) and hippocampus (left hippocampus: $F(1,14) = 9.04$, $P < 0.01$; right hippocampus: $F(1,14) = 5.61$, $P < 0.05$) was observed. No main effect of route direction (in- versus against-route items) and no significant interactions between the factors decision point and route direction were observed. All brain areas showing an effect of decision points and their location of peak activation, expressed in millimeters as Talairach coordinates are reported in Table 2.

To test for effects of route direction we compared in-route items with against-route items. This comparison showed increased activity in the left superior parietal lobe (Fig. 3A), the right middle temporal gyrus (Fig. 3B), the right caudate nucleus (Fig. 3C), as well as in the anterior cingulate gyrus (Fig. 3D). To investigate whether, apart from an effect of route direction, these areas showed decision-point-related responses as well, region of interest analyses were performed (see Experimental procedures). An ANOVA of the averaged beta-weights from the left superior parietal lobe (Fig. 3A) showed the expected effect of route direction ($F(1,14) = 7.75$, $P < 0.01$) only. No main effect of decision point and no significant interaction between the factors were observed. An ANOVA of the averaged beta-weights from the right middle temporal gyrus (Fig. 3B) showed besides an effect of route direction ($F(1,14) = 34.89$, $P < 0.001$) no effect of decision point and no interaction. An ANOVA of the averaged beta-weights from the right caudate head showed no other effects, apart from a main effect of route direction ($F(1,14) = 11.73$, $P < 0.01$). An ANOVA of the averaged beta-weights from the anterior cingulate gyrus (Fig. 3D) showed, besides an effect of route direction ($F(1,14) = 25.08$, $P < 0.001$), a main effect of decision point ($F(1,14) = 4.65$, $P < 0.05$). No significant interaction between the factors was observed. All brain areas showing an effect of route direction and their location of peak activation, expressed in millimeters as Talairach coordinates are reported in Table 3.

Whole brain analysis of the interaction of the factors decision point and route direction showed increased activity in the left cerebellum. The Talairach coordinates were $x = -6$, $y = -37$, $z = -32$. The size of the region was 90 mm^3 . An ANOVA of the averaged beta-weights from this region showed the expected significant interaction between both factors only ($F(1,14) = 7.15$, $P < 0.01$). No main effects were observed. A further area observed for this contrast was the anterior cingulate gyrus ($x = 0$, $y = -4$, $z = 28$). This area did not exceed the cluster size threshold (see methods). No other brain areas showing increase activity for the interaction were observed.

Table 1 – Probability of means and standard deviations of recognition performance in the retrieval phase

Objects from mazes		Distractor objects	
Hits	Misses	Correct rejections	False alarms
0.59±0.16	0.41±0.16	0.85±0.10	0.15±0.10

3. Discussion

In the present study, fMRI was used to investigate the neural representation of route knowledge. We investigated the brain areas involved in a representation of route direction, and

a representation of decision points. These issues were assessed using a subliminal spatial priming paradigm after participants had learned a route through a virtually simulated museum. The results provide clear evidence for two separate memory systems for object location and route direction.

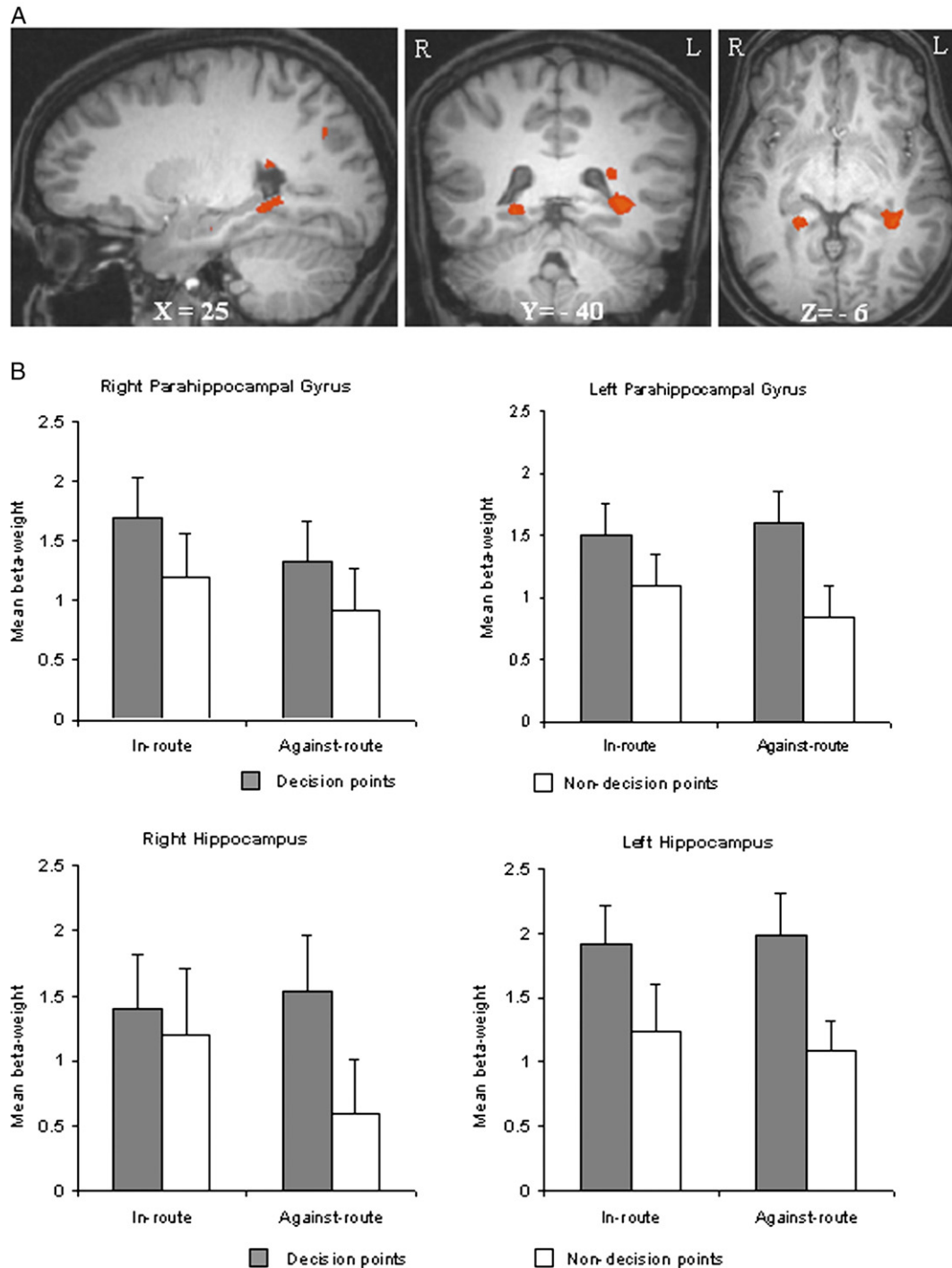


Fig. 2 – Increased neural activity for decision-point objects. (A) Increased activity was observed in bilateral parahippocampal gyrus for decision-point as compared to non-decision point objects. Location of peak activation, expressed in millimeters as Talairach coordinates was $x = -29$, $y = -40$, $z = -6$ for the left and $x = 25$, $y = -40$, $z = -6$ for the right parahippocampal gyrus ($p < 0.001$). (B) Regionally averaged beta-weights for the left and the right parahippocampal gyrus and the left and right hippocampus showing increased activity for decision as compared to non-decision point objects separately for in- and against-route items. Bars indicate standard errors across participants.

Table 2 – Increased brain activity for decision as compared to non-decision point items

Anatomical region	Talairach coordinates			Brodmann area	Volume (mm ³)	Z-score
	x	y	z			
<i>Right</i>						
Medial aspect of frontal lobe	5	52	0	10	205	3.87
Paracentral lobule	10	–21	44	4	187	3.67
Amygdaloid nucleus	17	–9	–13	34	658	3.56
Superior parietal lobule	23	–70	31	19	168	3.80
Parahippocampal gyrus	25	–44	–2	36	358	3.96
Hippocampus	22	–9	–16		293	3.56
Gyrus occipitalis medius	32	–75	14	18	1162	4.63
Postcentral gyrus	40	–23	23	40	519	3.80
Superior temporal gyrus	55	–3	0	20	1050	3.78
<i>Left</i>						
Medial occipital gyrus	–33	–80	13	18	1210	5.42
Parahippocampal gyrus	–31	–39	–6	36	296	4.00
Hippocampus	–27	–36	–1		744	3.98
Superior parietal lobule	–27	–41	56	7	455	3.65
Superior frontal gyrus	–20	–1	40	6	612	3.72
<i>p</i> < 0.001 (uncorrected).						

The in-scanner behavioral results showed no effect of decision point and route direction. In two behavioral experiments (see Supplementary data), effects of decision point and route direction were observed. In general, response time effects for decision points and route direction are small and the different outcomes could result from overall shorter response times in the fMRI experiment. These shorter response times could have prevented the detection of small differences between the conditions. Additionally, the circumstances in the behavioral experiments and in the MRI scanner are different. However, the brain clearly shows differential effects of decision point and route direction which demonstrate that the experimental manipulation was effective. Previous results (Janzen and van Turennout, 2004) showed that navigationally relevant objects are represented in the parahippocampal gyrus for forgotten as well as correctly remembered objects. This automatic storage even without conscious awareness of having seen an object before shows that the neural representation of decision points is independent of behavioral responses.

The brain imaging data showed increased activity in bilateral parahippocampal gyrus and hippocampus for decision as compared to non-decision-point items. The increase in activity for decision-point objects in the parahippocampal gyrus is in line with previous findings (Janzen and van Turennout, 2004; Janzen et al., 2007). The parahippocampal gyrus is an area involved in scene representation and object-place associations (Bar and Aminoff, 2003; Epstein et al., 2003; Maguire et al., 1998), but is also activated by objects in isolation if they have previously been recognized in a spatial context (Janzen and van Turennout, 2004).

Different from our previous fMRI results the present data showed a decision-point effect not only in the parahippocampal gyrus but also in bilateral hippocampus. This additional activity in the hippocampus is most likely related to the priming task used in the present study, which is more complex than the previously used simple object recognition

task. Participants are presented with a masked prime-object and a target-object. Prime- and target-objects had followed each other in or against the traveled direction on a previously seen route for both decision- and non-decision-point objects. The temporal-spatial relation between prime and target object could therefore be responsible for the hippocampal activity.

The temporal lobe including the hippocampus and the parahippocampal gyrus has been shown to be involved in the coding of spatial information in an allocentric frame of reference (Shelton and Gabrieli, 2002). FMRI data have suggested that different frames of reference can be linked to differential patterns of neural activation (e.g., Burgess et al., 2002). The hippocampus has been proposed to be involved in the creation of allocentric representations (e.g., Ekstrom et al., 2003; O'Keefe and Nadel, 1978).

The data suggest a representation of objects at decision points in an allocentric frame of reference. In order to provide a successful wayfinding mechanism, navigationally relevant information like decision points would be most helpful if they are represented in allocentric coordinates independent of the egocentric orientation in an environment. Our findings provide support for an allocentric representation of navigationally relevant landmarks.

To investigate memory for route direction, items consisting of prime-target combinations that immediately followed each other in the direction of the previously seen route were compared to items with prime-target combinations against the traveling direction. Contrasting the two conditions revealed a network of areas including the left inferior parietal lobe, the anterior right middle temporal gyrus, the right caudate head, and the anterior cingulate gyrus (Fig. 3).

The parietal lobe is involved in coding spatial information in an egocentric frame of reference (Burgess et al., 1999). The traveling direction makes direct use of the body and is therefore likely to be represented in egocentric coordinates. The increase in the left inferior parietal lobe

(Fig. 3A) for in- as compared to against-route items provides evidence for a coding of route direction in an egocentric frame of reference.

Additional to the left inferior parietal lobe, the head of the right caudate nucleus was significantly more activated for in- as compared to against-route items. Postle and

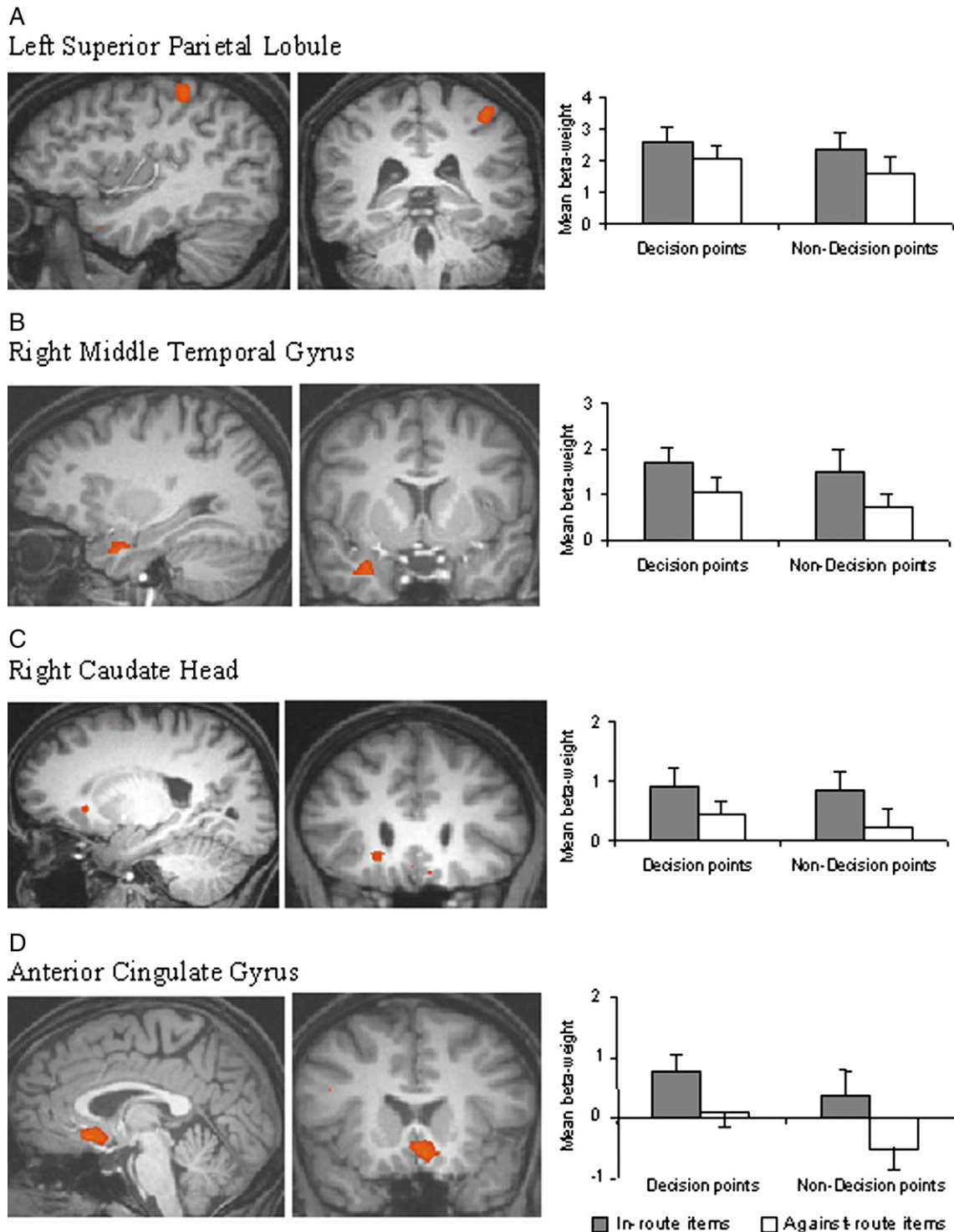


Fig. 3 – Increased activity for in- as compared to against-route items. Locations of peak activation are expressed in millimeters as Talairach coordinates. Regionally averaged beta-weights showing increased activity for in- as compared to against-route items separately for decision and non-decision point items. Bars indicate standard errors across participants. (A) Increased activity in the left inferior parietal lobe ($x=-39$, $y=-35$, $z=50$; $p<0.001$). (B) Increased activity in the right middle temporal gyrus ($x=28$, $y=6$, $z=-19$; $p<0.001$). (C) Increased activity in the right caudate head ($x=21$, $y=23$, $z=3$; $p<0.001$). (D) Increased activity in the anterior cingulate ($x=-2$, $y=16$, $z=-3$; $p<0.001$, BA 25). Regionally averaged beta-weights showed increased activity for in- as compared to against-route items as well as increased activity for decision as compared to non-decision point items.

Table 3 – Increased brain activity for in- as compared to against-route items

Anatomical region	Talairach coordinates			Brodmann area	Volume (mm ³)	Z-score
	x	y	z			
<i>Right</i>						
Middle temporal gyrus	28	6	-19	38	472	4.48
Right caudate head	21	23	3		108	3.78
<i>Left</i>						
Inferior parietal lobe	-39	-35	50	40	618	4.41
Anterior cingulate	-2	16	-3	25	1136	4.5

$p < 0.001$ (uncorrected).

D'Esposito (2003) found greater neural activity in the caudate nucleus when contrasting egocentric trials with allocentric trials in a spatial working memory task. Furthermore, the caudate nuclei have been found to represent stimulus–response (S–R) associations (Iaria et al., 2003; Packard and Knowlton, 2002) and are involved in route recognition (Hartley et al., 2003; Voermans et al., 2004). Iaria et al. (2003) found the hippocampus and the caudate nucleus differentially involved with the hippocampus being active during the use of a place-learning strategy and the caudate nucleus during the use of S–R associations. Routes can be stored by linking objects in terms of S–R chains (Bohbot et al., 2004; Iaria et al., 2003). In this context, the representation of the traveled direction describes how to get from one landmark to the other with a stronger S–R association in the traveled direction as compared to the reverse direction.

The right anterior medial temporal lobe, including the entorhinal and perirhinal cortices, showed increased neural activity for in- as compared to against-route items. This brain area has been shown to be involved in spatial tasks. The entorhinal cortex that receives a major part of its input through two different streams originating from the perirhinal cortex and parahippocampal gyrus is itself the biggest input into the hippocampus (e.g., Hargreaves et al., 2005). The parahippocampal gyrus is likely to supply visuospatial information from the dorsal visual stream with which it is connected, such as information concerning object locations. The entorhinal cortex has been found to be involved in contextual learning (Burwell et al., 2004), in processing of geometric properties of the environment (Parron and Save, 2004), and in mediating between different types of navigational cues (Oswald et al., 2003). Recent data (for an overview see McNaughton et al., 2006) show a new class of neurons called grid cells in the rat entorhinal cortex that provide a topographically organized map of a spatial environment. In conjunction with head direction cells, they provide a representation not only of spatial location but also of distance and direction. This evidence suggests that the entorhinal cortex supports the binding of different types of spatial information. Our results (Fig. 3B) showed increased activity in the human anterior medial temporal lobe including the entorhinal cortex. Although the resolution of fMRI data does not allow distin-

guishing between entorhinal and perirhinal and parahippocampal cortex, an involvement of entorhinal cells in the representation of route direction is likely.

In the present study, the cingulate region including the subgenual gyrus showed increased activity when contrasting in- with against-route items. Additionally, this area showed a significantly stronger activity for decision-point items. Thus, this region is the only brain area representing not only the traveling direction but also objects placed in navigationally relevant locations. Previous findings (e.g., Paus et al., 1993; Posner, 1994) have suggested that the dorsal anterior cingulate cortex (ACC) is a neurobiological substrate for executive control of cognitive and motor processes whereas the ventral ACC is involved in affective and emotional processes (for a review see Bush et al., 2000; Somerville et al., 2006). This involvement of the ventral cingulate region might reflect that the participants are more pleased when prime and target object follow each other in the previously learned order. Further research is necessary to investigate the function of the ventral cingulate region in the representation of route knowledge.

The whole brain analysis of the interaction of the factors decision point and route direction showed increased activity in the left cerebellum. Recent evidence shows the cerebellum involved in spatial tasks and in integrating different information (e.g. Burguière et al., 2005; Egner and Hirsch, 2004; Leggio et al., 2000). Egner and Hirsch (2004) showed increased activity in the cerebellum when participants performed a Stroop task. The authors conclude that the cerebellum is amongst other brain regions involved in cognitive control and integration of information. Future research should investigate the exact role of the cerebellum in integrating different kinds of spatial information.

In conclusion, our data shows the existence of two separate memory systems that represent navigationally relevant object location like decision points and the traveling direction of a route. How both types of spatial information are integrated needs to be further investigated. First evidence is presented that suggests that the cerebellum is involved in the interaction of the two memory systems. Distinct memory systems and an efficient integration of different spatial information could provide a basis for successful wayfinding.

4. Experimental procedures

4.1. Participants

Fifteen healthy human adults (7 women and 8 men) gave informed written consent before participating in the experiment. They were financially compensated for their efforts. All participants were right-handed according to self-report. Mean age was 22.6 years (range 19–31 years). The study was approved by the CMO Committee on Research Involving Human Subjects (Region Arnhem-Nijmegen).

4.2. Stimulus material and procedures

The experiment was divided into two parts: a study phase outside the MR scanner, and a recognition phase during

which functional images of the whole brain were acquired. Participants were given the following standardized written instruction for the study phase: ‘You apply for a job in a museum that exhibits belongings of famous people. You will be guided through two sections of the museum. The exhibits are placed on tables along the wall. Please learn the objects and the route.’

The architecture software (3D TraumhausDesigner 4.0, Data Becker GmbH & CO.KG) was used to create the film sequences through a virtual reality museum presented on a 1.60 GHz-M Pentium 4 personal computer with 512 MB of RAM and a 15.0-in. XGA LCD Screen. The virtual museum consisted of two mazes of the same shape. In each maze 72 three-dimensional, colored objects were placed on tables. In total, 144 different objects were included in the mazes. In real world dimensions, each maze had a length of 279 ft and was 112 ft wide in relation to a simulated eye level of 5.6 ft. The two mazes were shown in separate film sequences, lasting 8.5 min each.

Objects were placed at decision points (D-objects) or at non-decision points (ND-objects). Decision points were right-angled intersections; non-decision points were simple right angled turns. In the film sequences, a right or left turn was made both at decision and non-decision points. This way, the effects of motion were not confounded with those of navigational relevance. Participants had no control over the timing in the virtual environment to ensure that the amount of time spent at decision and non-decision points was matched (an object was visible on average 5 s in the visual focus and 11 s total).

Subsequently, fMRI time series were obtained while participants performed a recognition task. In this recognition phase, participants were instructed to indicate as accurately and as quickly as possible whether they had seen the target object in the former film sequences by pressing either a yes or a no response key. Responses were given with the index and the middle finger of the right hand. A single trial (Fig. 1B) consisted of a fixation cross centered on the screen for 500 ms, followed by a mask for 800 ms and a prime-object for 43 ms. Afterwards a second mask followed for 400 ms and a target-object for 500 ms. Then, a jittered inter-stimulus interval between 3000 and 5000 ms in steps of 250 ms followed, counterbalanced over conditions. Prime- and target-object were shown from a canonical perspective on a white background. Thus, during scanning, no maze-related information was presented. A total number of 288 trials were included in the recognition task. All trials were presented rapidly, in a randomly intermixed order to prevent participants from anticipating and changing strategies for the different event types. The masks used for subliminal presentation were created by mosaic-scrambling an image containing proximally 20 items. In total, 12 masks were created based on three of these images.

The experiment included eight conditions consisting of 36 trials each. Four conditions consisted of objects that were included in the previously seen mazes with the correct answer ‘yes’. These conditions follow a 2×2 factorial design: D-objects primed by a preceding D-object (in-route), D-objects primed by a succeeding D-object (against-route), ND-objects primed by a preceding ND-object (in-route), ND-objects

primed by a succeeding ND-object (against-route). Furthermore, four distractor conditions (the correct answer is ‘no’) were included: distractor-objects (not included in the museum) primed by D-objects, distractor-objects primed by ND-objects, distractor-objects primed by distractor-objects, and a low-level baseline condition consisting of scrambled objects. Mean word frequency as well as frequency range was equal for all sets of objects.

4.3. MRI data acquisition

A 3-T MRI system (Siemens TRIO, Erlangen, Germany) was used to acquire functional images of the whole brain. Using a gradient-echo echo planar scanning sequence 36 axial slices were obtained for each participant (voxel-size 3×3×3 mm³, TR=2290 ms, field of view=192, TE=30 ms, flip angle=75°). All functional images were acquired in one run that lasted for 45 min. Following the acquisition of functional images a high-resolution anatomical scan (T1-weighted MP-RAGE, 176 slices) was acquired.

4.4. Functional MRI data analysis

fMRI data were analyzed using BrainVoyager QX (Brain Innovation, Maastricht, The Netherlands). Functional images were corrected for motion and slice scan time acquisition. Data were temporally smoothed with a high pass filter removing frequencies below 3 cycles per time course. Functional images were coregistered with the anatomical scan and transformed into Talairach coordinate space using the 9-parameter landmark method of Talairach and Tournoux (1988). Images were spatially smoothed with a FWHM Gaussian kernel of 6 mm.

Statistical analyses were performed in the context of the general linear model, including eight effects of interests and confounds. Event-related hemodynamic responses for each of the different event types were modeled as delta functions convolved with a synthetic hemodynamic response function. Prime and target were modeled together as one event type with the event-onset at the prime object. The statistical threshold at the voxel level was set at $p < 0.001$, uncorrected for multiple comparisons. To reject false positive activity, effects were considered significant if they exceeded a cluster-size threshold of at least 50 mm³. (see Forman et al., 1995). Both fixed as well as random-effects group analyses were performed. Specific effects were tested by applying linear contrasts to the parameter estimates for each event as obtained in the random effects group analyses. Region of interest analyses of the temporal lobe were performed as follows: First, we functionally defined the region by selecting all voxels showing an effect of decision versus non-decision points in the fixed effects group analysis. Then, we obtained the beta-weights (i.e., the regression coefficients) as indexes of effect size for all voxels included in these regions of interest, separately for all individual subjects, for each of the event types. To investigate whether apart from the main effect of the fMRI comparison, additional effects and interactions could be observed, we analyzed the regionally averaged beta-weights in repeated-measurement ANOVAs. Specific effects were

tested by applying *t*-contrasts to the regionally averaged beta-weights obtained for the different event types. Region of interest analyses for the effect of route direction were defined by the comparison between in- versus against-route items. The averaged beta-weights out of these regions were analyzed using the same procedure.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.brainres.2007.05.074](https://doi.org/10.1016/j.brainres.2007.05.074).

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