Spatial and temporal aspects of navigation in two neurological patients

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We present two cases (A.C. and W.J.) with navigation problems resulting from parieto-occipital right hemisphere damage. For both the cases, performance on the neuropsychological tests did not indicate specific impairments in spatial processing, despite severe subjective complaints of spatial disorientation. Various aspects of navigation were tested in a new virtual reality task, *the Virtual Tübingen task*. A double dissociation between spatial and temporal deficits was found; A.C. was impaired in route ordering, a temporal test, whereas W.J. was impaired in scene recognition and route continuation, which are spatial in nature. These findings offer important insights in the functional and neural architecture of navigation. *NeuroReport* 21:685–689 **© 2010 Wolters Kluwer Health | Lippincott Williams & Wilkins.**

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Introduction

Impairments in spatial navigation and topographical memory can occur after right hemisphere damage, in particular to the hippocampus [1–3]. It has been argued that the hippocampus underlies our ability to keep track of viewpoint shifts and to build an allocentric representation of space, which concerns the locations of objects relative to their surrounding regardless of the observer's position [4]. Other elements of the navigational process include landmark recognition and ordering, and representation of heading [5,6], which seem to involve the parietal areas.

Clearly, navigation is a complex cognitive process and deficits in this process may follow from a multitude of neurological damage. This is shown by the two cases of patients suffering from parieto-occipital cortical right hemisphere damage reported in this study. They came to our attention as a result of self-reported difficulties with navigation in particular. Given the complex nature of navigation, it is of importance to test it by examining the separate elements to find out where those impairments lie exactly. In addition, it was of particular interest to see whether these two cases would show different types of impairments, as their self-reported complaints concerning navigation were somewhat different. Patient A.C. does recognize the environment but is unable to find her way to another location. In contrast, patient W.J. does not recognize her environment but manages to reach her destination if she is forced to try.

The reported impairments of both the patients could not be seen with standard neuropsychological testing. None of these tests seemed to be specific enough to identify the impaired ability. Therefore, the aim of this study was to design an experiment that would allow us to selectively identify the impairments of these two patients. We composed a task battery consisting of new and existing tasks, to test navigation in particular, and spatial and temporal cognitive processes at a more general level. The main task reported here was a new virtual reality task inspired by earlier research [7], with which we tested four different abilities required for successful navigation. This allowed us to find out whether selective impairments of navigation abilities can occur.

Case history

Case A.C.

A.C. is a 36-year-old right-handed woman with Hebrew as her native language and Dutch as her second language, which she speaks fluently. Not long after the birth of her third child, she started losing her way at random moments. She could be driving or walking through an environment she was very familiar with, when she suddenly forgot which way to go. On account of the frightening nature of these episodes, she was first diagnosed with an anxiety disorder. When a neurological examination was performed, a lesion was detected in the right hemisphere in the superior part of the parietal cortex, which was diagnosed as an ischaemic infarction. The lesioned areas were the medial occipital, the angular and a small part of the postcentral gyrus.

During a general neuropsychological examination, one standardized test, the Stylus Maze test, provided some evidence for her self-reported impairment. This test also

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showed her use of compensatory strategies; she verbalized every turn and kept repeating them in the correct order to memorize them. Only when the route was too long to be memorized verbally, her performance dropped to an impaired level. Her impairment was most likely so hard to assess because of her compensation strategies. The main conclusion of the general neuropsychological examination was impairment in visuospatial functioning and a limited storage capacity.

Case W.J.

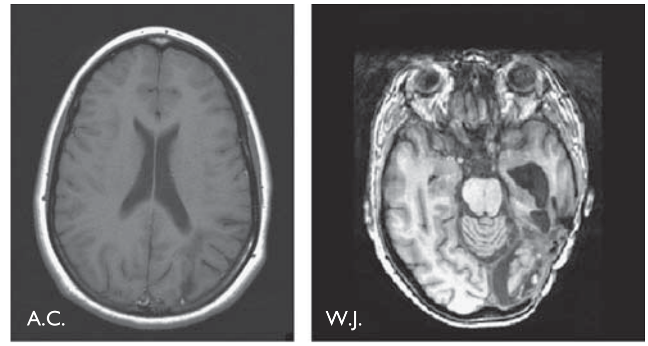
Patient W.J. is a right-handed, 44-year-old woman with an education level similar to A.C. She had been diagnosed with a brain tumour (glioblastoma multiforme) and had undergone multiple surgeries. The lesions were in the posterior region of the right hemisphere; the occipital, temporal and the superior parietal areas were damaged, along with the fusiform gyrus and the hippocampus. During an experiment focusing on her hemianopsia, she reported to have problems specifically related to navigation. She described to have trouble planning ahead and remembering locations. Well-known routes were not a problem for her, but when she walked in a less familiar environment she would have trouble with what the next turn would be. This problem increased if she was riding her bicycle because of the higher speed of movement. She reported to be fearful of unannounced roadblocks and very insecure in new environments. Her strategy mostly entailed an elaborate observation of her surroundings and actively picturing the route from different viewpoints.

Methods

Participants

As A.C. and W.J. were comparable in sex, age and verbal and nonverbal intelligence, six control individuals were recruited to match both of them on these characteristics. In Table 1, the characteristics of both the cases and the controls are presented. In Fig. 1, the scans show the

Fig. 1



Magnetic resonance imaging scans indicating the lesion locations for A.C. and W.J. (both T1-weighted images).

lesions of both A.C. and W.J. All comparisons between the controls and both the patients separately were made using the Bayesian approach for single case studies, and all reported P values are Bayesian P values [8].

Table 1 Characteristics and neuropsychological test results of patients A.C. and W.J., and all control participants

	Controls		
	Mean (SD)	A.C.	W.J.
Age (y)	36.7 (2.81)	36	44
Education level	6.7 (0.52)	6	5*
Handedness score	18.33 (4.41)	22	24
Trail-making test	2.94 (2.35)	2.3	3.6
RAVLT: immediate recall	57.83 (2.70)	38**	49
RAVLT: delayed recall	14.00 (0.84)	9***	11**
Raven APM	10.33 (1.41)	9	9
Letter number sequencing (WAIS)	12.17 (1.6)	7*	10
Corsi block span forward	8.67 (1.21)	8	7
Corsi block span backward	9.83 (1.33)	8	4**

Raven APM, Raven advanced progressive matrices; RAVLT, Rey auditory verbal learning test.
*$P<0.05$.
**$P<0.01$.
***$P<0.001$.

Task design and procedure

Standard neuropsychological tests were used to assess overall intelligence and memory performance. Nonverbal intelligence was assessed with the 12-item short form of the Raven Advanced Progressive Matrices [9]. Verbal memory was assessed with the Dutch version of the Rey Auditory Verbal Learning Test (RAVLT) [10,11] and the Letter Number Sequencing task (Wechsler Adult Intelligence Scale-III) was used as an index of the verbal working memory [12]. The spatial working memory was evaluated by means of the forward and backward condition of the Corsi block-tapping task [13]. The trail-making test was used as a measure for visual attention and divided attention [14].

Navigation skills were assessed by the Virtual Tübingen task; a virtual reality environment of the town of Tübingen, Germany. The task consisted of several elements; the study phase, a scene recognition test, a route continuation test and a scene ordering test. Two partially overlapping routes were created in the virtual environment (Fig. 2). For both the routes, a movie was constructed in which the route was shown at a set speed equal to a comfortable walking speed. The participants viewed both the routes twice in the same order; first a long route (340 s), then a short route (302 s). After the study phase, the scene recognition was tested. The participants were shown 30 static images, half of which were stills taken from one of the movies and the other half was a collection of images taken from other points in the environment not visible in the movies (for example see Fig. 3). For each image, the participants were asked to indicate whether or not they had seen it before and if so, in which route. Seven images were taken from the short route and eight from the long route. The long and short

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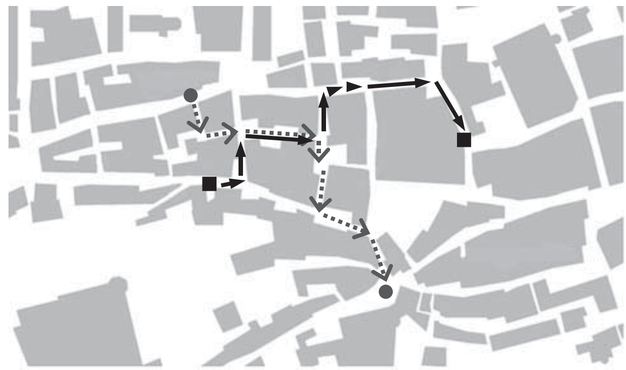
Fig. 2



A map of the virtual environment used in the Tübingen task. The black arrows indicate the long route and the dotted arrows the short route. An arrow is placed from every decision point (intersection) to the next. The squares and dots indicate the start and end points of the routes.

Fig. 3

An example of an image taken from one of the routes. This image is taken from the starting point of the long route.

routes were named the green and red route in all instructions to avoid confusion. The total score was the percentage of correctly answered trials. If a trial was correctly indicated as seen before but linked to the wrong route, it was marked as incorrect. The second test involved route continuation; for an image taken from one of the routes, the participants were asked to indicate whether the route continued with a left turn, straight ahead or a right turn. In total, 13 images were presented; six from the short route and seven from the long route. The last test concerned route ordering. A series of images were shown simultaneously on the screen, all taken from the same route. With mouse clicks, the participants indicated the correct order of the images when walking the route from start to finish. For the long route, nine images were presented, and eight for the short route. For each correctly ranked image, two points were given and one point was given for each image, one position too early or too late in the order.

Before the Tübingen task, a control task for the scene recognition test was presented, the object recognition test. Similar to the scene recognition test, the participants viewed a movie of a series of object images twice. Then, 60 images (30 new, 30 old) were presented separately, which were judged on whether or not they were present in the movie. Difficulty was set to match the scene recognition test for the controls in a pilot study. The speed of presentation was adjusted and the object identity of the objects in the new images was very similar to the objects in the movie, for example, a standard telephone and a cellular phone.

Throughout the experiment, the participants were comfortably seated in a darkened room in front of a large, wide-screen computer monitor (50 inch) at a distance of about 60 cm. The experimenter was present throughout the experiment to introduce the tests and repeat the instructions given on the screen if necessary. The tasks were presented in this fixed order to avoid unwanted training effects (e.g. stimuli presented during the continuation task could help performance on the recognition task if they were presented in this reversed order).

Apart from the Virtual Tübingen task, a series of new and existing tasks were used. The general outcome of these tasks will be reported as 'additional qualitative findings'.

Results

Neuropsychological tests

A.C. differs significantly from the controls on the RAVLT and Letter Number Sequencing task, most likely because she is a native Hebrew speaker, with Dutch as her second language. Her spatial working memory and abstract reasoning ability were at the same level as the controls, as measured by the Corsi and Raven tasks.

W.J. showed performance below the control's average on verbal recall and spatial working memory, as indicated by her RAVLT and Corsi scores. This is an indication of weaker working memory performance, for both verbal and spatial information. Estimates of general intelligence were comparable with the controls.

Virtual Tübingen task

The results of the object and scene recognition, route continuation and route ordering tests are given in Table 2. W.J.'s performance was significantly lower than the controls on both the recognition tests (both $P < 0.05$) and the route continuation test ($P < 0.01$). Her performance on the route ordering test was not different from the controls. An opposite pattern was found for A.C.; she was comparable with the controls on both the recognition tests and the route continuation test, whereas she was impaired on the route ordering test ($P < 0.01$). Apart from this double

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Table 2 Mean accuracy on the object recognition, scene recognition and route continuation tasks, and the mean score for the route ordering task (range possible scores 0–34)

	Controls		
	Mean (SD)	A.C.	W.J.
Object recognition	73 (5.46)	68	55*
Scene recognition	75 (7.04)	63	47*
Route continuation	85 (9.65)	77	38**
Route ordering	21.17 (3.25)	6**	16

*$P<0.05$.
**$P<0.01$.

dissociation pattern, both the patients were slightly worse on scene recognition compared with object recognition, whereas no difference was found among the controls.

Additional qualitative findings

We briefly mention some general, qualitative findings for both the cases from the other spatial and temporal tasks that were used. A.C. performed well on most of the spatial tasks, even at an above average level in some cases. She was very motivated and extensively used verbal memorization. The few impairments found mainly concerned navigation, in either a virtual or real life situation. One striking deficit was her estimation of the length of a tone, her estimation was 14.4 s too long as compared with an average of 2.92 for the five control participants ($P<0.001$). In contrast, she was at an average level in the other temporal tasks concerning reproduction and production. When she was asked to estimate the absolute distance of the routes (15–70 m) after walking them, she was clearly overestimating and underestimating but her relative distance estimation was intact.

W.J. showed a more general pattern of impairment. She performed poorly on a number of spatial perception and spatial working memory tasks. W.J. was also impaired on absolute time estimation, but not as strongly as A.C. (W.J. = 4.25, A.C. = 14.4, controls = 2.92).

Discussion

The aim of this study was to objectively assess the self-reported problems in navigation in the two patients. As the standard neuropsychological testing material was insufficient to identify these problems, we used the new Virtual Tübingen task in which multiple aspects of navigation were tested within a virtual environment. A.C. and W.J. were very similar in personal characteristics and gave similar selective, but not identical accounts about their problems with finding their way. Importantly, there was no sign of any major cognitive impairment in either patient, which could significantly decrease the reliability of these findings.

The data indicated a clear double dissociation of the spatial and temporal features of navigation; W.J. was significantly impaired on scene and object recognition and on route continuation, whereas A.C. was impaired on route ordering. W.J.'s problems with scene and object recognition can be easily explained by her general deficit in working memory, verbal and spatial, which was absent in A.C. Route continuation concerns linking a decision point to a direction, and therefore, can also be considered as a spatial working memory aspect of navigation. In contrast, route ordering was the only test that clearly required temporal knowledge of the route, as the participants indicated the order of appearance of a set of images. A.C.'s impairment was restricted to the temporal aspect of navigation, whereas W.J. only showed impaired performance on the spatial tests.

A.C.'s case, therefore, provides evidence that the angular and postcentral gyri might have a role in temporal processing specifically, which was also supported by her substantial problems with temporal duration estimation. These brain areas could be part of an extended brain circuitry including the (midparietal) precuneus (see Ref. [15]), which may play a vital role in temporal order processing [16,17]. Importantly, the observed temporal deficits cannot be ascribed to an impairment of sequencing, as A.C. could order numbers, and numbers and letters flawlessly in the trail-making test. Of note, spatial information processing and memory can still be spared when damage to the fore-mentioned areas occurs. In contrast, the considerable temporal, occipital and some parietal damage found in W.J. led to impairment on a number of spatial tasks, not only on tasks directly related to navigation. The fact that the performance for route ordering was spared in her case, could be explained by the forced nature of the test. As it was evident that all the images were from the actual route, she had to just point out the correct order. This also fits her own descriptions; if she was forced to choose a route, she would eventually manage to end up at the correct location.

The double dissociation found for these two cases shows a division of the spatial and temporal aspects of navigation. This novel distinction helps to understand the functional architecture of navigation behaviour. Importantly, it resembles a similar distinction made for episodic memory [18] and general memory in a group of Korsakoff patients [19]. It has been suggested that the spatial and temporal features of episodic memory rely on separate processing systems [18], which is fully in line with the double dissociation of the two cases presented here. This separation of space and time could well be a pivotal factor in studies concerning navigation ability, as a correct representation of both spatial and temporal information seems to be crucial for successful navigation.

Conclusion

The ability to navigate consists of both the spatial and temporal processes, which rely on separate mechanisms as is proven by the double dissociation in the task performance of the two patients. The Virtual Tübingen task testing these processes provides a useful tool to look further into those mechanisms and their neural correlates.

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