Neuropsychologia 103 (2017) 154–161

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

A systematic investigation of navigation impairment in chronic stroke patients: Evidence for three distinct types

Michiel H.G. Claessen[a,b,c,*], Johanna M.A. Visser-Meily[b,d], Tobias Meilinger[e], Albert Postma[a], Nicolien K. de Rooij[b], Ineke J.M. van der Ham[c]

[a] *Experimental Psychology, Helmholtz Institute, Utrecht University, The Netherlands*
[b] *Center of Excellence in Rehabilitation Medicine, Brain Center Rudolf Magnus, University Medical Center Utrecht, and De Hoogstraat Rehabilitation, The Netherlands*
[c] *Department of Health, Medical and Neuropsychology, Leiden University, The Netherlands*
[d] *Department of Rehabilitation, Physical Therapy Science & Sports, Brain Center Rudolf Magnus, University Medical Center Utrecht, The Netherlands*
[e] *Max Planck Institute for Biological Cybernetics, Tübingen, Germany*

ARTICLE INFO

Keywords:
Spatial navigation
Stroke
Virtual reality
Landmark
Location
Path

ABSTRACT

Objective: In a recent systematic review, Claessen and van der Ham (2017) have analyzed the types of navigation impairment in the single-case study literature. Three dissociable types related to landmarks, locations, and paths were identified. This recent model as well as previous models of navigation impairment have never been verified in a systematic manner. The aim of the current study was thus to investigate the prevalence of landmark-based, location-based, and path-based navigation impairment in a large sample of stroke patients.
Method: Navigation ability of 77 stroke patients in the chronic phase and 60 healthy participants was comprehensively evaluated using the Virtual Tübingen test, which contains twelve subtasks addressing various aspects of knowledge about landmarks, locations, and paths based on a newly learned virtual route. Participants also filled out the Wayfinding Questionnaire to allow for making a distinction between stroke patients with and without significant subjective navigation-related complaints.
Results: Analysis of responses on the Wayfinding Questionnaire indicated that 33 of the 77 participating stroke patients had significant navigation-related complaints. An examination of their performance on the Virtual Tübingen test established objective evidence for navigation impairment in 27 patients. Both landmark-based and path-based navigation impairment occurred in isolation, while location-based navigation impairment was only found along with the other two types.
Conclusions: The current study provides the first empirical support for the distinction between landmark-based, location-based, and path-based navigation impairment. Future research relying on other assessment instruments of navigation ability might be helpful to further validate this distinction.

1. Introduction

Spatial navigation is the complex ability that allows us to familiarize ourselves with new environments and to find our way around in environments that we already know (Wolbers and Hegarty, 2010). This ability is crucial to many tasks we encounter daily, such as driving from home to work (and back), reaching the kitchen from the living room in our own home or visiting someone in an unfamiliar city.

The importance of navigation ability in daily life activities is clearly illustrated by brain-injured patients who report difficulties with navigation as a consequence of their brain damage. For instance, nearly a third of chronic stroke patients complain about such difficulties. Their self-reported navigation problems were associated with significant reductions of autonomy and quality of life (van der Ham et al., 2013). Impaired navigation ability has not only been reported in stroke patients (Busigny et al., 2014; van Asselen et al., 2006), but also in patient groups with traumatic brain injury (Livingstone and Skelton, 2007), mild cognitive impairment and Alzheimer's disease (Cushman et al., 2008; deIpolyi et al., 2007), and Korsakoff's syndrome (Oudman et al., 2016). While navigation impairment might directly result from brain injury as in these patient groups, there are also healthy individuals who never properly developed the ability to navigate (Developmental Topographical Disorientation; DTD) (Iaria and Burles, 2016).

Navigation ability has increasingly been recognized as a highly complex cognitive construct and relying upon the integration of many cognitive mechanisms (Brunsdon et al., 2007; Ekstrom et al., 2014;

---

* Correspondence to: Department of Health, Medical, and Neuropsychology, Leiden University, Wassenaarseweg 52, 2333 AK Leiden, The Netherlands.
E-mail address: m.h.g.claessen@fsw.leidenuniv.nl (M.H.G. Claessen).

http://dx.doi.org/10.1016/j.neuropsychologia.2017.07.001
Received 11 March 2017; Received in revised form 13 June 2017; Accepted 1 July 2017

Wiener et al., 2009; Wolbers and Hegarty, 2010). Clinical researchers have therefore attempted to verify whether qualitatively distinct types of navigation impairments exist depending on the specific cognitive mechanisms affected. These clinical studies can be roughly divided into two approaches: the single-case study approach and the group study approach. Single-case studies are applied on a regular basis in neuropsychology (McIntosh and Brooks, 2011) and have proven to be highly important for the study of navigation impairment. Case studies usually provide a specific pattern of impaired and intact navigation skills in individual brain-injured patients with navigation-related complaints. In 1999, Aguirre and D'Esposito published a comprehensive review of the single-case literature on navigation impairment (Aguirre and D'Esposito, 1999). They distinguished between four types of impairments: egocentric disorientation (an inability to represent locations with regard to the body), heading disorientation (an inability to derive directional information from landmarks), landmark agnosia (an inability to identify prominent features in the environment or to use these for orientation), and anterograde disorientation (an inability to learn new routes and environments). Their review has had a profound influence on the study of navigation impairment in brain-injured patients through case studies in particular. However, the prevalence of these distinct types of navigation impairment has never been investigated in systematic studies based on groups of brain-injured patients.

As many new case studies on navigation impairment have been published since 1999 (e.g., Caglio et al., 2011; Ciaramelli, 2008; Ruggiero et al., 2014; van der Ham et al., 2010), there was an increasing need for an updated analysis of the types of navigation impairments as described in this literature. Such an analysis has obvious theoretical implications for the cognitive architecture of navigation ability, but it would also offer guidance to assessment of navigation ability in clinical practice. A recent paper has therefore provided such an update through a systematic literature review (Claessen and van der Ham, 2017). Detailed analysis of all relevant case reports revealed three main types of navigation impairments; deficits in landmark, location, and path knowledge.

Landmark-based navigation impairment entails problems with navigation due to defective processing of landmarks or environmental scenes (see also van der Ham et al., 2017). Patients with location-based navigation impairment suffer from defective acquisition and/or recall of knowledge about landmark locations and how these places relate to each other. They are likely to fail when asked to indicate the absolute or relative locations of landmarks or to point into their directions when (imagining) standing at a particular location. They also have difficulties with drawing correct maps and with providing accurate route descriptions between locations. Path-based navigation impairment, the most complex category, is associated with difficulties regarding knowledge about the paths that connect locations. Consequently, patients might experience problems in using maps or spatial information alone (e.g., the metrical structure of paths) for the purpose of navigation. Similar to patients with location-based navigation impairment, they might be unable to provide correct maps and route descriptions. While some overlap between location and path knowledge is evident, the case report on patient T.T. (Maguire et al., 2006) shows that they can be dissociated. T.T's navigation problems occur when he has to use the fine-grained structure of paths between London landmarks, but he is accurate when he can rely on main roads only. This performance pattern suggests intact knowledge of locations, while his knowledge of non-main roads is compromised.

When explicitly comparing Aguirre and D'Esposito's taxonomy and the new model by Claessen and van der Ham, several notable dissimilarities and similarities become evident. Methodologically, the model is different in that it results from a systematic literature search, while Aguirre and D'Esposito's taxonomy was inspired by case descriptions in the literature in a nonsystematic way. From a conceptual viewpoint, substantial overlap exists between the categories of “landmark agnosia” and “landmark-based navigation impairment”. In the taxonomy, however, landmark problems should occur in both novel and familiar environments to reach a diagnosis of “landmark agnosia”. Recent evidence has shown that selective landmark problems confined to novel environments alone can also occur (van der Ham et al., 2017), which is more in line with the new model. The category of “heading disorientation” appears to incorporate elements of both location-based and path-based navigation impairment. Patients suffering from “egocentric disorientation” are interpreted by Claessen and van der Ham as suffering from a global spatial deficit, a basic problem with positioning their bodies in space, rather than navigation impairment. Finally, the importance assigned to the occurrence of navigation problems in novel environments alone or in both familiar and novel environments differs between the taxonomy and the new model. While this factor is important for reaching a diagnostic category in the taxonomy, the new model is primarily centered around three functionally distinct types of navigation impairment related to landmarks, locations, and paths.

Apart from the single-case study approach, navigation impairment has also been investigated more systematically in group studies on brain-injured patients. The rigorous and large-scale approach of such studies has attracted attention to navigation problems in several neurological disorders. Group studies have also contributed to knowledge on the neurocognitive architecture of navigation ability by correlating navigation performance to lesion characteristics (see e.g., Barrash et al., 2000; Busigny et al., 2014; van Asselen et al., 2006). Strikingly, the group study approach has never been applied to systematically and empirically validate the types of navigation impairment as suggested by the single-case study literature. To our knowledge, not a single group study has ever provided a systematic evaluation of Aguirre and D'Esposito's model in a large sample of brain-injured patients, let alone the model as recently described by Claessen and van der Ham (2017).

Hence, the current study was intended to provide a systematic assessment of the three types of navigation impairment. Given the frequent occurrence of navigation impairment after stroke (Busigny et al., 2014; van Asselen et al., 2006; van der Ham et al., 2013), navigation ability in a virtual reality setting was systematically assessed using the Virtual Tübingen (VT) test in a large group of stroke patients in the chronic phase (see e.g., Claessen et al., 2016a; Claessen et al., 2016d). The VT test is a valid measure of real-world navigation ability in stroke patients (Claessen et al., 2016b) and is comprised of twelve subtasks that are frequently used in the navigation literature (e.g., Arnold et al., 2013; Busigny et al., 2014; Liu et al., 2011; Maguire et al., 1996; Sorita et al., 2013; van Asselen et al., 2006). It contains, for example, subtasks for scene recognition, the order of turns, metrical characteristics of the route, and route drawing. The concepts addressed by the subtasks can be linked to the three types of navigation impairment related to landmarks, locations, and paths (see Section 2.3). Based on the patients' VT subtask performances, the prevalence of each type of navigation impairment will be determined. While the three types of navigation impairment are expected to be dissociable (i.e., can occur in isolation), they are not necessarily exclusive. It is therefore anticipated that some patients will suffer from more than one type of navigation impairment.

While the VT test has shown to be a valid measure of real-world navigation ability, it is not necessarily the case that each impaired score on a VT subtask reflects significant navigation problems in daily life. Therefore, the Wayfinding Questionnaire (WQ; Claessen et al., 2016c; de Rooij et al., in press), a self-report instrument for navigation-related complaints, was first administered to select patients who suffer from navigation problems in daily life. In this way, we ensured that only VT subtask performances were analyzed of patients that reflect clinically meaningful deficits.

2. Method

2.1. Participants

Eighty-one stroke patients, living in the community, were recruited from rehabilitation center De Hoogstraat Revalidatie Utrecht and the rehabilitation department of the University Medical Center Utrecht (the Netherlands). Patients were considered eligible to participate when they could walk independently and no indications of severe aphasia or neglect were evident. None of the healthy controls suffered from any visual, neurological, psychiatric, or mobility problems and did not report a history of substance abuse. When willing to participate, participants provided written informed consent after the nature of the study was explained. They received monetary compensation for study participation.

Study approval was provided by the medical ethical committee of the University Medical Center Utrecht (the Netherlands; protocol no. 12–198) and the study design complied with the Declaration of Helsinki. The data presented here are part of a larger project into navigation ability in stroke patients. Portions of this data set have been used in earlier studies (Claessen et al., 2016b, 2016d; de Rooij et al., in press).

2.2. Procedure and materials

Participants were invited to rehabilitation center De Hoogstraat (Utrecht, the Netherlands) for assessment. Participants were asked to complete the Wayfinding Questionnaire (WQ) and were subjected to a cognitive screening based on four common neuropsychological tasks. Participants then performed an extensive navigation test, the Virtual Tübingen (VT) test. When a short break was requested, it was held between the cognitive screening and the VT test. No breaks were allowed during the VT test to prevent differences in the time span between watching the virtual route and the administration of the VT subtasks across participants.

2.2.1. Wayfinding questionnaire

The Wayfinding Questionnaire (WQ) is a self-report instrument for navigation-related complaints (Claessen et al., 2016c; de Rooij et al., in press; van der Ham et al., 2013). The latest version of the WQ contains 22 items divided over three subscales: "Navigation and Orientation" (11 items, e.g., "I can always orient myself quickly and correctly when I am in an unknown environment"), "Spatial Anxiety" (8 items, e.g., "I am afraid of losing my way somewhere"), "Distance Estimation" (3 items, e.g., "Without a map, I can estimate the distance of a route I have walked well, when I walk it for the first time"). Scores range from 1 to 7. Higher numbers indicate high navigation ability and low spatial anxiety. The internal validity of the WQ (i.e., its factor structure and reliability) has proven to be very high in both stroke patients and healthy controls. Also, the three-facture structure of the WQ has been found to be eligible for interpretation and analysis of response patterns in both of these groups (see Claessen et al., 2016c). The discriminant validity of the WQ has been supported by showing that patients with low WQ scores perform worse than patients with normal WQ scores on a virtual navigation test battery (de Rooij et al., in press). The English version of the WQ can be obtained from the Appendix in Claessen et al. (2016c).

2.2.2. Cognitive screening

The cognitive screening consisted of four common neuropsychological tasks. These tasks were chosen to gain a general indication of the participants' cognitive status. Administration was in the following fixed order:

- The Dutch version of the Adult Reading Test was applied to measure premorbid intelligence (Schmand et al., 1992). An estimated premorbid intelligence quotient was obtained by adjusting the raw score for age, gender, and educational level.
- The Corsi Block-Tapping Task served as a measure of visuospatial attention span (forward condition: Kessels et al., 2000) and visuospatial working memory span (backward condition: Kessels et al., 2008).
- The Trail Making Test (TMT; Reitan, 1992) was administered to obtain measures of mental processing speed (part A) and divided attention (part B).
- Verbal short-term memory was measured using the Digit Span subtest of the WAIS-III (Wechsler, 1997).

2.2.3. Virtual Tübingen test

The Virtual Tübingen (VT) test (Claessen et al., 2016a, 2016b, 2016d; van der Ham et al., 2010) comprised a learning phase and a test phase. In the learning phase, participants watched a movie depicting a route through a realistic virtual reproduction of the German city Tübingen twice (van Veen et al., 1998). They were instructed to remember as much as possible from the route.

Two different routes were developed that were counterbalanced across participants (see Fig. 1a in Claessen et al., 2016b, for a map). The routes were highly comparable in duration (210 and 253 s), and equal in distance (analogous to 400 m), speed (slightly above walking speed), and the number of decision points (seven actual left and right turns and straight ahead on four decision points). A laptop (17.3-in. diagonal HD4 display) was used to present the movie.

After having watched the virtual route two times, the test phase started. The full VT test battery consisted of twelve subtasks, directly related to the studied virtual route. Subtasks were administered in the following fixed order:

1. *Scene Recognition.* Twenty-two images (1075 × 806, 68 dpi) of decision points taken from VT (see Fig. 1 for an example) were presented to the participants one-by-one in random order. Half of these images were encountered during the route, whereas the other half depicted scenes in VT that were not shown in the route. The participants' task was to indicate whether the images were part of the studied route. Accuracy: number of correct responses, range: 0–22.
2. *Route Continuation.* Eleven decision points taken from the route were presented one-by-one in random order to the participants. They were requested to indicate in what direction the route continued at each decision point. Accuracy: number of correct responses, range: 0–11.
3. *Route Sequence.* Participants had to indicate the sequence of turns as taken during the route. They were instructed to do so by using printed arrows. Only actual turns (i.e., left and right turns) were taken into account. Accuracy: number of correctly indicated turns in the sequence, range 0–7.
4. *Route Order.* A set of eleven printed images was provided with the instruction to reconstruct the order in which the scenes were encountered in the route. Scoring: Three points were awarded for each scene assigned to its correct position in the sequence; two points for scenes assigned one position too late or too early; a single point for scenes two positions away from correct placement, range 0–33.
5. *Route Progression.* Participants were shown one-by-one eleven images taken from the route accompanied by a piece of paper with a printed line (17.8 cm) on it. They were asked to mark the location of the presented scene on the line which represented the total distance of the route. Scoring: an averaged deviation score was calculated over eleven trials, range 0–1. A score of 1 represented perfect performance.
6. *Route Distance.* Participants were shown scenes taken from the route in pairwise fashion. Each trial was accompanied by a printed line along with the instruction to mark the distance between the two scenes relative to the total length of the route. Scoring: an averaged deviation score was calculated over nine trials, range 0–1. A score of 1 represented perfect performance.
7. *Pointing to Start.* Participants were shown eleven images from the route in one-by-one fashion. They were asked to point to the

Fig. 1. Impression of Virtual Tübingen.

starting point of the route for each scene using a rotational device. Scoring: average deviation of degrees from the correct response, range: 0–180 degrees.

8. *Pointing to End.* Similar to subtask 7, but here participants were required to point to the end point of the route using the rotational device. Scoring: average deviation of degrees from the correct response, range: 0–180 degrees.
9. *Distance Estimation.* Participants were requested to estimate the distance of the route. Scoring: absolute deviation from the correct response (400 m) in meters, regardless of underestimation or overestimation.
10. *Duration Estimation.* Participants were asked to estimate the duration of the route as shown in the movie. Scoring: absolute deviation in seconds from the correct response (route A: 210 s; route B: 253 s), regardless of underestimation or overestimation.
11. *Route Drawing.* Participants were provided with a schematic map of VT and asked to draw the route on it. Only the starting point and the correct direction were shown. Scoring: one point was awarded for each correctly indicated turn (left, straight forward, or right) at relevant decision points, range: 0–11.
12. *Map Recognition.* Participants were requested to select the correct map of the route out of four options. Scoring: correct or incorrect.

Subtasks 1, 2, 7, and 8 were assessed on a laptop using Presentation software (version 16.3; Neurobehavioral Systems). All other subtasks were paper-and-pencil tasks.

2.3. VT subtask classification

Performance on the VT test was interpreted based on the model presented by Claessen and van der Ham (2017). This model has described three main types of navigation impairments related to knowledge about landmarks, locations, and paths. The VT subtasks assess aspects of these types of knowledge and can be linked to the model in the following way: landmark knowledge (Scene Recognition), location knowledge (Pointing to Start, Pointing to End), and path knowledge (Route Continuation, Route Sequence, Route Order, Route Progression, Route Distance, Distance Estimation, Duration Estimation, Route Drawing, Map Recognition). Path knowledge was extensively represented in the VT test, which is directly related to the complexity of the concept of “path”.

2.4. Statistical analysis

Demographic characteristics of patients and controls were compared: age, educational level (independent *t*-tests), and gender distribution (chi square test). Independent *t*-tests assessed group differences on the neuropsychological tasks. Next, to compare performance of patients and controls on the VT subtasks, univariate analyses of covariance with educational level as a covariate were conducted for each subtask. Due to the nominal scale of the Map Recognition subtask (correct or incorrect), a chi square test was applied to test whether patients and controls differed in their performance. Effect sizes of significant results are reported as Pearson's *r* (small = 0.10–0.29, medium = 0.30–0.49, large ≥ 0.50) or partial eta squared (η_ρ^2; small = 0.01–0.05, medium = 0.06–0.12, large ≥ 0.13). The number of participants with an impaired score on each subtask was calculated by converting subtest scores to *z*-scores based on means and standard deviations of the control group. It is a common approach in neuropsychology to mark the lowest 5% of performances as impaired (Binder et al., 2009), which corresponds to *z*-scores lower than –1.64 *SD* of the mean of the control group.

All *p*-values of ≤ 0.05 were considered statistically significant. The statistical procedures were performed using SPSS version 23.0.

3. Results

3.1. Demographics and cognitive screening

Data of five participants was excluded from the data set. Three patients and one healthy control reported a severe lack of motivation during testing and one patient suffered from serious motion sickness during the VT test. The final study sample thus consisted of 77 patients (*M* = 59.9 years, *SD* = 12.1, range = 22–81 years, 58% males) and 60 healthy controls (*M* = 58.5 years, *SD* = 9.8, range = 37–87 years, 47% males). The groups were comparable in terms of age ($t < 1$) and gender

Table 1
Stroke types and lesion locations in the patient group ($n = 77$).

	n (%)
Stroke type	
Ischemic stroke	60 (77.9%)
Hemorrhagic stroke	
- Intracerebral	13 (16.9%)
- Subarachnoid	3 (3.9%)
Unknown	1 (1.3%)
Stroke location	
Supratentorial region	
- Left	31 (40.3%)
- Right	32 (41.5%)
- Bilateral	2 (2.6%)
Infratentorial region	
- Left	2 (2.6%)
- Right	2 (2.6%)
- Bilateral	7 (9.1%)
Unknown	1 (1.3%)

Note. Classification is based on the characteristics of the first stroke event. Six patients (7.8%) suffered from two stroke events and two patients (2.6%) from three stroke events.

($\chi^2 = 1.88$, $p = 0.171$). Patients had an educational level of 5.2 (*SD* = 1.4) (Verhage 1964; possible range = 1–7) and the educational level of controls was 5.6 (*SD* = 0.9); this difference was not statistically significant but reached trend level ($t = -1.90$, $df = 131.35$, $p = 0.059$). Educational level was therefore entered as covariant in the group comparisons between patients and controls on VT subtask performances. Information on time between first stroke event and study participation was available for 74 patients and varied between 6 and 98 months ($M = 37.2$; $SD = 16.3$). Stroke characteristics of the patient group are displayed in Table 1.

The scores of patients on all neuropsychological tasks were significantly lower than that of healthy controls (see Table 2). The corresponding effect sizes ranged from small ($r = 0.18$) to medium ($r = 0.46$).

3.2. Group performance on the VT test

Group performance on the VT subtasks is displayed in Table 3. Results of univariate analyses of covariance with educational level as a covariate indicate that controls significantly outperformed patients on five out of twelve VT subtasks: Scene Recognition, Route Continuation, Route Order, Route Progression, and Route Drawing. The corresponding effect sizes ranged from small ($\eta_p^2 = 0.040$) to medium ($\eta_p^2 = 0.115$). For each subtask, the percentage of patients and controls who obtained an impaired score (< –1.64 *SD* of the controls' mean) was also calculated. The percentage of impaired scores was higher in the patient group on all subtasks except for Pointing to Start (controls: 8.8% impaired; patients: 8.1% impaired).

Table 2
Performance on the cognitive screening tests in patients and controls.

	Patients	Controls	*t*	*p*	Effect size *r*
Dutch Adult Reading Test (IQ)	97.7 (17.1)	109.7 (11.5)	–4.85	< .001***	0.39
Corsi Block-Tapping Task					
- forward (span × score)	37.0 (15.1)	42.0 (12.4)	–2.08	.040*	0.18
- backward (span × score)	38.2 (19.9)	48.0 (16.4)	–3.14	.002**	0.26
Trail Making Test					
- Part A (seconds)	58.2 (38.1)	35.1 (11.5)	5.04	< .001***	0.46
- Part B (seconds)	142.4 (109.0)	74.9 (26.1)	5.18	< .001***	0.49
- Part B (B / A)	2.7 (1.6)	2.2 (0.6)	2.24	.027*	0.22
Digit Span (WAIS-III)					
- forward (score)	7.5 (1.9)	9.0 (1.6)	–4.86	< .001***	0.39
- backward (score)	5.0 (2.0)	6.2 (2.0)	–3.37	.001**	0.28

Note. Standard deviations are displayed in parentheses.
* $p < .05$.
** $p < .01$.
*** $p < .001$; Pearson's *r* effect size: small = 0.10–0.29, medium = 0.30–0.49, large ≥ 0.50.

3.3. Analysis of individual performance patterns on the VT test

Our intention was to analyze only VT performance patterns of patients who suffer from navigation problems in daily life to ensure that impaired VT subtask scores reflect clinically meaningful deficits. Therefore, responses on the Wayfinding Questionnaire (subscales: Navigation and Orientation, Spatial Anxiety, and Distance Estimation) were used to select patients who experience significant navigation problems. Thirty-three out of the 77 patients (43%) obtained at least one impaired WQ-subscale score (< –1.64 *SD* of the controls' mean) and were selected for further analysis of their VT performance pattern. More specifically, eighteen patients obtained a single impaired WQ-subscale score, and two and three impaired WQ-subscale scores were found in eight and seven patients, respectively.

As described in Section 2.4, VT performance patterns of the selected 33 patients were evaluated by converting subtest scores to *z*-scores based on means and standard deviations of the control group. All *z*-scores lower than –1.64 *SD* of the mean of the control group were marked as an impaired score. The results of this analysis are displayed in Fig. 2, indicating that all three types of navigation impairments were identified by the VT test battery and in various combinations in these 33 patients. Both landmark-based (three patients) and path-based navigation impairment (twelve patients) occurred in isolation. Although no patient suffered from location-based navigation impairment alone, this type co-occurred with path-based navigation impairment (three patients). A combination of navigation impairments related to landmarks and paths was also relatively common (six patients). Navigation impairment due to combined deficits in all three domains (i.e., landmarks, locations, and paths) was established in two patients. No objective evidence of navigation impairment was found for the remaining seven patients. Overall, navigation impairments related to paths occurred much more often (23 patients) than landmark-based (eleven patients) and location-based navigation impairment (five patients).

An overview of the lesion location, the impaired WQ subscale scores, and the impaired VT subtask scores for each patient is provided in Supplementary Table 1.

4. Discussion

The primary objective of this study was to provide a systematic inventory of the prevalence of landmark, location, and path-based navigation impairments, which have recently been identified in a systematic literature review summarizing all relevant single-case reports on this topic (Claessen and van der Ham, 2017). In the current study, it was hypothesized that these impairments can occur in isolation (as they are dissociable by definition), but might co-occur as well. This aim was addressed by analyzing the individual performance patterns of 33 stroke patients with significant navigation-related complaints on a comprehensive virtual navigation test battery. Based on this analysis, objective evidence of both overall and selective navigation impairments was established for 26 patients. Both landmark-based and path-based navigation impairment were found to occur in isolation, while location-based navigation impairment was only established in combination with the other two types. Overall, these results provide a first systematic validation of the distinction between landmark, location, and path-based navigation impairment.

Table 3
Performance on the Virtual Tübingen test battery in patients and controls.

VT subtask (*n* controls, *n* patients)	Controls *M* (*SD*)	Patients *M* (*SD*)	*p*	η_p^2	Controls % Impaired	Patients % Impaired
Scene Recognition (60,77)	17.9 (2.2)	16.6 (2.4)	.003**	0.066	8.3	20.8
Route Continuation (60,77)	8.2 (1.8)	6.9 (2.0)	.001**	0.090	6.7	20.8
Route Sequence (60,77)	3.9 (2.0)	3.4 (2.0)	.152	0.015	0.0	5.2
Route Order (60,77)	18.7 (7.2)	14.6 (6.5)	.001**	0.081	5.0	14.3
Route Progression (60,77)	0.83 (0.07)	0.77 (0.08)	< .001***	0.115	3.3	26.0
Route Distance (59,77)	0.80 (0.08)	0.78 (0.08)	.133	0.017	3.4	10.4
Distance Estimation (60,76)	1175.8 (1107.2)	1461.8 (1323.1)	.235	0.011	6.7	14.5
Duration Estimation (60,76)	340.9 (728.0)	401.0 (753.5)	.698	0.001	6.7	7.9
Pointing to Start (57,74)	51.1 (21.6)	57.4 (20.9)	.168	0.015	8.8	8.1
Pointing to End (57,74)	62.5 (22.5)	68.1 (25.8)	.230	0.011	6.8	10.8
Route Drawing (60,77)	5.2 (3.1)	3.9 (3.0)	.019*	0.040	1.7	13.0
Map Recognition (60,77)	33 correct (55%)	32 correct (42%)	.125	–	–	–

Note. Possible scoring range: Scene Recognition = 0–22, Route Continuation = 0–11, Route Sequence = 0–7, Route Order = 0–33, Route Progression = 0–1, Route Distance = 0–1, Distance Estimation = Absolute deviation from correct response in meters, Duration Estimation = Absolute deviation from correct response in seconds, Pointing to Start and Pointing to End = Deviation from correct response in degrees, Route Drawing = 0–11, and Map Recognition = correct or incorrect.

* $p < .05$.

** $p < .01$.

*** $p < .001$; partial eta squared (η_p^2) effect size: small = 0.01–0.05, medium = 0.06–0.12, large ≥ 0.13.

Path-based navigation impairment was clearly very common, as it occurred in 23 out of the 26 patients with objective evidence of navigation impairment (either in isolation or along with the other types). This finding might result from the fact that nine out of twelve VT subtasks address some form of path knowledge. Indeed, this might have increased the chances of finding an impaired score on a subtask related to path knowledge as compared to subtasks assessing landmark and location knowledge. It should, however, be emphasized that path-based navigation impairment is the most complex type of navigational knowledge (Claessen and van der Ham, 2017). Path knowledge does not solely entail concrete information such as the order of landmarks or turns, but can also be enriched with abstract, metric information about the size of turning angles and segment lengths (Chrastil and Warren, 2014; Mallot and Basten, 2009; Meilinger, 2008).

Some discussion is also needed regarding the finding that no patient in the current study sample suffered from an isolated location-based navigation impairment. However, there appeared to be some overlap between navigation impairments related to locations and paths, as three patients were found to suffer from a combination of these types of navigation impairment. This accords both with the nature of the tasks that were used to measure location knowledge (Pointing to Start and Pointing to End) as well as the partial conceptual overlap between knowledge about locations and paths. In each trial of the pointing tasks, participants were provided with a scene and required to indicate the position of the starting or end point of the route. By showing them scenes in these tasks, path knowledge might have been measured in addition to location knowledge alone, as this task is mostly likely solved by mentally "walking back" or "walking on" to the starting or end point of the route. This strategy directly points out the connection between path and location knowledge. It has been suggested that location knowledge about the interrelationships of multiple locations results from egocentric updating (i.e., integration of paths; Claessen and van der Ham, 2017; Ino et al., 2007), mental imagery (Byrne et al., 2007) or mental model construction (Meilinger, 2008). More specifically, Meilinger (2008) has proposed the existence of a hierarchical relationship between path and location knowledge, as location knowledge (needed to solve pointing tasks) is only inferred online in working memory directly from path knowledge. Overall, it appears advisable that future research further explores the relationship between path and location knowledge and, if possible, develops more direct measures of location knowledge to better establish location-based navigation impairment.

Some comments on the model by Claessen and van der Ham (2017) and its relation to previous models on navigation ability are in order. The model builds both on these previous models and current issues in the literature. Several decades ago, Siegel and White (1975) introduced the landmark-route-survey-model. While they argued that these three types of knowledge were sequentially accumulated and increasing in

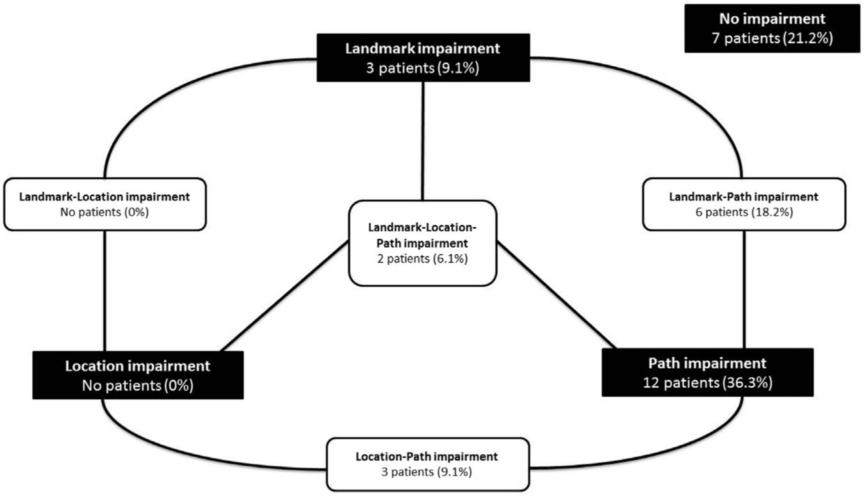

Fig. 2. The prevalence of the three types of navigation impairments as measured with the Virtual Tübingen test in 33 stroke patients with complaints of navigation problems.

difficulty, neither the sequential properties proposed in their model have been supported empirically (Ishikawa and Montello, 2006), nor does the model take the use of egocentric and allocentric perspectives into account (Zhong and Kozhevnikov, 2016). This is a limitation of the landmark-route-survey model, given that others have identified egocentric and allocentric perspective taking as a key element of navigation ability (e.g., Nardini et al., 2006). Such studies tend to focus on orientation in space, or location knowledge, rather than the dynamic process of moving through an environment. The proposed model by Claessen and van der Ham (2017) shows for the first time how egocentric and allocentric perspective use can be integrated with both route and survey knowledge.

Regarding clinical implications of the present study, the two navigation ability instruments used, the WQ and the VT test, appear to be invaluable for use in clinical practice. They can help to assess navigation impairment in a brain-injured patient in a stepwise manner. If a patient presents with navigation-related complaints, the WQ can be used to first establish whether these complaints are of substantial nature (Claessen et al., 2016c; de Rooij et al., in press). Ideally, the next step entails the administration of an actual navigation test. The VT test serves this purpose by providing the clinician with a detailed profile of navigational strengths and weaknesses of the patient (Claessen et al., 2016b). Applying the WQ and VT test in clinical practice leads to better insight in the specific type of navigation impairment a patient is suffering from, which is in turn important for selecting the appropriate treatment approach (see below).

Lastly, the finding that the three navigation impairment types can occur independently also has important implications for the cognitive rehabilitation of impairments in this function. It is now common practice in cognitive rehabilitation to teach patients to approach tasks in an alternative way; a compensatory strategy, by enabling them to rely on their cognitive strengths (Ponds and Hendriks, 2006; Wilson, 2002). There is recent evidence that the application of compensatory strategies might also be effective in the context of rehabilitating navigation impairment. A group of researchers has taught a patient to apply an external compensation strategy to overcome his navigation problems by using a smartphone with GPS technology (Rivest et al., 2016). Another study has supported the feasibility of internal compensation to rehabilitate navigation impairment by teaching six patients to apply an alternative navigation strategy based on individual cognitive strengths (Claessen et al., 2016a). This latter approach in particular, which regards navigation ability as a complex rather than a unitary function, accords with the finding that the three types of navigation ability are dissociable.

The current study is characterized by a number of strengths. To the best of our knowledge, it provides the first systematic inventory of the types of navigation impairment that have been identified in the single-case literature on this topic. The focus was on patients with mild stroke (i.e., stroke patients who have participated in outpatient rehabilitation programs or those who show quick neurological recovery during inpatient rehabilitation). Mild stroke is not only the most common type of stroke; its prevalence is also expected to increase further due to the availability of better treatment options (Rochette et al., 2007). People with mild stroke usually live at home independently and are therefore reliant on adequate navigation ability. Another strength of this study is that a relatively large group of stroke patients was comprehensively tested on their navigation abilities. In addition, WQ responses were used to select only patients with significant navigation complaints. This procedure ensured that impaired subtask scores on the VT reflect clinically meaningful results.

Several limitations also need to be discussed. Information on the neuropsychological functioning of the patient sample was somewhat limited. To ensure that the duration and mental strain of the test procedure was feasible for them, the cognitive screening was restricted to neuropsychological tasks for premorbid intelligence, visuospatial attention span and working memory, verbal short-term memory, mental processing, and divided attention. While stroke patients with severe forms of neglect were not included, it should be mentioned that information about representational neglect would have been informative given that navigation impairment has been associated with neglect in mental imagery (Guariglia et al., 2005). A final possible critique concerns the fact that information on lesion locations was highly limited for many stroke patients (see Claessen et al., 2016d, for further explanation), therefore it was not possible to link the types of navigation impairments to lesion locations. The current study was therefore specifically devoted to the identification of the three functionally dissociable types of navigation impairments related to landmarks, locations, and paths. Further research into the neurocorrelates of landmark, location and path-based navigation impairments is, however, strongly recommended.

In conclusion, the current study has provided empirical evidence for the distinction between three types of navigation impairments related to landmarks, locations, and paths. This provides the first validation of the model that has recently been put forward by Claessen and van der Ham (2017) based on a systematic review of single-case studies on navigation impairment. This evidence was established in the current study by systematically assessing navigation ability related to landmarks, locations, and paths in stroke patients using the VT test battery. Both landmark and path-based navigation impairment were found in isolation, whereas navigation impairment related to locations was only objectified in combination with the other types. Future research relying on other assessment instruments of navigation ability than the VT test might help to further validate this model.

Acknowledgements

We were supported by a “Meerwaarde” grant of the Netherlands Organization for Scientific Research (NWO, 840.11.006) and a grant of the “Revalidatiefonds” (R2012090) in conducting this study. IH was supported by a Veni grant (NWO, 451-12-004). We have no conflicts of interest to declare.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2017.07.001.

References

Aguirre, G.K., D'Esposito, M., 1999. Topographical disorientation: a synthesis and taxonomy. Brain 122, 1613–1628. http://dx.doi.org/10.1093/brain/122.9.1613.

Arnold, A.E.G.F., Burles, F., Krivoruchko, T., Liu, I., Rey, C.D., Levy, R.M., Iaria, G., 2013. Cognitive mapping in humans and its relationship to other orientation skills. Exp. Brain Res. 224 (3), 359–372. http://dx.doi.org/10.1007/s00221-012-3316-0.

van Asselen, M., Kessels, R.P.C., Kappelle, L.J., Neggers, S.F.W., Frijns, C.J.M., Postma, A., 2006. Neural correlates of human wayfinding in stroke patients. Brain Res. 1067 (1), 229–238. http://dx.doi.org/10.1016/j.brainres.2005.10.048.

Barrash, J., Damasio, H., Adolphs, R., Tranel, D., 2000. The neuroanatomical correlates of route learning impairment. Neuropsychologia 38 (6), 820–836. http://dx.doi.org/10.1016/S0028-3932(99)00131-1.

Binder, L.M., Iverson, G.L., Brooks, B.L., 2009. To err is human: "abnormal" neuropsychological scores and variability are common in healthy adults. Arch. Clin. Neuropsychol. 24, 31–46. http://dx.doi.org/10.1093/arclin/acn001.

Brunsdon, R., Nickels, L., Coltheart, M., 2007. Topographical disorientation: towards an integrated framework for assessment. Neuropsychol. Rehabil. 17 (1), 34–52. http://dx.doi.org/10.1080/09602010500505021.

Busigny, T., Pagès, B., Barbeau, E.J., Bled, C., Montaut, E., Raposo, N., Pariente, J., 2014. A systematic study of topographical memory and posterior cerebral artery infarctions. Neurology 83, 996–1003. http://dx.doi.org/10.1212/WNL.0000000000000780.

Byrne, P., Becker, S., Burgess, N., 2007. Remembering the past and imagining the future: a neural model of spatial memory and imagery. Psychol. Rev. 114, 340–375. http://dx.doi.org/10.1037/0033-295X.114.2.340.

Caglio, M., Castelli, L., Cerrato, P., Latini-Corazzini, L., 2011. Pure topographical disorientation in a patient with right occipito-temporal lesion. Neurosciences 16, 60–65.

Chrastil, E.R., Warren, W.H., 2014. From cognitive maps to cognitive graphs. PLoS One 9, e112544. http://dx.doi.org/10.1371/journal.pone.0112544.

Ciaramelli, E., 2008. The role of ventromedial prefrontal cortex in navigation: a case of impaired wayfinding and rehabilitation. Neuropsychologia 46, 2099–2105. http://dx.doi.org/10.1016/j.neuropsychologia.2007.11.029.

Claessen, M.H.G., van der Ham, I.J.M., 2017. Classification of navigation impairment: a systematic review of neuropsychological case studies. Neurosci. Biobehav. Rev. 73, 81–97. http://dx.doi.org/10.1016/j.neubiorev.2016.12.015.

Claessen, M.H.G., van der Ham, I.J.M., Jagersma, E., Visser-Meily, J.M.A., 2016a. Navigation strategy training using virtual reality in six chronic stroke patients: a novel and explorative approach to the rehabilitation of navigation impairment. Neuropsychol. Rehabil. 26 (5–6), 822–846. http://dx.doi.org/10.1080/09602011.2015.1045910.

Claessen, M.H.G., Visser-Meily, J.M.A., de Rooij, N.K., Postma, A., van der Ham, I.J.M., 2016b. A direct comparison of real-world and virtual navigation performance in chronic stroke patients. J. Int. Neuropsychol. Soc. 22 (4), 467–477. http://dx.doi.org/10.1017/S1355617715001228.

Claessen, M.H.G., Visser-Meily, J.M.A., de Rooij, N.K., Postma, A., van der Ham, I.J.M., 2016c. The Wayfinding Questionnaire as a self-report screening instrument for navigation-related complaints after stroke: internal validity in healthy respondents and chronic mild stroke patients. Arch. Clin. Neuropsychol. 31 (8), 839–854. http://dx.doi.org/10.1093/arclin/acw044.

Claessen, M.H.G., Visser-Meily, J.M.A., Jagersma, E., Braspenning, M.E., van der Ham, I.J.M., 2016d. Dissociating spatial and spatiotemporal aspects of navigation ability in chronic stroke patients. Neuropsychology 30 (6), 697–807. http://dx.doi.org/10.1037/neu0000260.

Cushman, L.A., Stein, K., Duffy, C.J., 2008. Detecting navigational deficits in cognitive aging and Alzheimer disease using virtual reality. Neurology 71, 888–895. http://dx.doi.org/10.1212/01.wnl.0000326262.67613.fe.

deIpolyi, A.R., Rankin, K.P., Mucke, L., Miller, B.L., Gorno-Tempini, M.L., 2007. Spatial cognition and the human navigation network in AD and MCI. Neurology 69, 986–997. http://dx.doi.org/10.1212/01.wnl.0000271376.19515.c6.

van der Ham, I.J.M., Kant, N., Postma, A., Visser-Meily, J.M.A., 2013. Is navigation ability a problem in mild stroke patients? Insights from self-reported navigation measures. J. Rehabil. Med. 45, 429–433. http://dx.doi.org/10.2340/16501977-1139.

van der Ham, I.J.M., Martens, M.A.G., Claessen, M.H.G., van den Berg, E., 2017. Landmark agnosia: evaluating the definition of landmark-based navigation impairment. Arch. Clin. Neuropsychol. 32 (4), 472–482. http://dx.doi.org/10.1093/arclin/acx013.

van der Ham, I.J.M., van Zandvoort, M.J.E., Meilinger, T., Bosch, S.E., Kant, N., Postma, A., 2010. Spatial and temporal aspects of navigation in two neurological patients. NeuroReport 21, 685–689. http://dx.doi.org/10.1097/WNR.0b013e32.

Ekstrom, A.D., Arnold, A.E., Iaria, G., 2014. A critical review of the allocentric spatial representation and its neural underpinnings: toward a network-based perspective. Front. Human. Neurosci. 8, 1–15.

Guariglia, C., Piccardi, L., Iaria, G., Nico, D., Pizzamiglio, L., 2005. Representational neglect and navigation in real space. Neuropsychologia 43, 1138–1143. https://doi.org/10.1016/j.neuropsychologia.2004.11.021.

Iaria, G., Burles, F., 2016. Developmental topographical disorientation. Trends Cogn. Sci. 20, 720–722. http://dx.doi.org/10.1016/j.tics.2016.07.004.

Ino, T., Doi, T., Hirose, S., Kimura, T., Ito, J., Fukuyama, H., 2007. Directional disorientation following left retrosplenial hemorrhage: a case report with fMRI studies. Cortex 43, 248–254. http://dx.doi.org/10.1016/S0010-9452(08)70479-9.

Ishikawa, T., Montello, D.R., 2006. Spatial knowledge acquisition from direct experience in the environment: individual differences in the development of metric knowledge and the integration of separately learned places. Cogn. Psychol. 52, 93–129. http://dx.doi.org/10.1016/j.cogpsych.2005.08.003.

Kessels, R.P.C., Van Zandvoort, M.J.E., Postma, A., Kappelle, L.J., De Haan, E.H.F., 2000. The Corsi Block-Tapping Task: standardization and normative data. Appl. Neuropsychol. 7 (4), 252–258. http://dx.doi.org/10.1207/S15324826AN0704_8.

Kessels, R.P.C., den Berg, Van, Ruis, E., C, Brands, A.M.A., 2008. The backward span of the Corsi Block-Tapping Task and its association with the WAIS-III Digit Span. Assessment 15 (4), 426–434. http://dx.doi.org/10.1177/1073191108315611.

Liu, I., Levy, R.M., Barton, J.S.S., Iaria, G., 2011. Age and gender differences in various topographical orientation strategies. Brain Res. 1410, 545–559. http://dx.doi.org/10.1016/j.brainres.2011.07.005.

Livingstone, S.A., Skelton, R.W., 2007. Virtual environment navigation tasks and the assessment of cognitive deficits in individuals with brain injury. Behav. Brain Res. 185 (1), 21–31. http://dx.doi.org/10.1016/j.bbr.2007.07.015.

Maguire, E.A., Burke, T., Phillips, J., Staunton, H., 1996. Topographical disorientation following unilateral temporal lobe lesions in humans. Neuropsychologia 34 (10), 993–1001. http://dx.doi.org/10.1016/0028-3932(96)00022-X.

Maguire, E.A., Nannery, R., Spiers, H.J., 2006. Navigation around London by a taxi driver with bilateral hippocampal lesions. Brain 129, 2894–2907. http://dx.doi.org/10.1093/brain/awl286.

Mallot, H.A., Basten, K., 2009. Embodied spatial cognition: biological and artificial systems. Image Vis. Comput. 27, 1658–1670. http://dx.doi.org/10.1016/j.imavis.2008.09.001.

McIntosh, R.D., Brooks, J.L., 2011. Current tests and trends in single-case neuropsychology. Cortex 47, 1151–1159. http://dx.doi.org/10.1016/j.cortex.2011.08.005.

Meilinger, T., 2008. The network of reference frames theory: a synthesis of graphs and cognitive maps. In: Freksa, C., Newcombe, N., Gärdenfors, P., Wölfl, S. (Eds.), Spatial Cognition VI: Learning, Reasoning, and Talking About Space. Springer, Berlin, pp. 344–360.

Nardini, M., Burgess, N., Breckenridge, K., Atkinson, J., 2006. Differential developmental trajectories for egocentric, environmental and intrinsic frames of reference in spatial memory. Cognition 101, 153–172. http://dx.doi.org/10.1016/j.cognition.2005.09.005.

Oudman, E., van der Stigchel, S., Nijboer, T.C.W., Wijnia, J.W., Seekles, M.L., Postma, A., 2016. Route learning in Korsakoff's syndrome: residual acquisition of spatial memory despite profound amnesia. J. Neuropsychol. 10, 90–103. http://dx.doi.org/10.1111/jnp.12058.

Ponds, R.W.H.M., Hendriks, M., 2006. Cognitive rehabilitation of memory problems in patients with epilepsy. Seizure 15, 267–273. http://dx.doi.org/10.1016/j.seizure.2006.02.011.

Reitan, R.M., 1992. Trail Making Test. Manual for Administration and Scoring. Reitan Neuropsychological Laboratory, Tucson, AZ.

Rivest, J., Svoboda, E., McCarthy, J., Moscovitch, M., 2016. A case study of topographical disorientation: behavioral intervention for achieving independent navigation. Neuropsychol. Rehabil (in press), Epub ahead of print. http://dx.doi.org/10.1080/09602011.2016.1160833.

Rochette, A., Desrosiers, J., Bravo, G., St-Cyr/Tribble, D., Bourget, A., 2007. Changes in participation after a mild stroke: quantitative and qualitative perspectives. Top. Stroke Rehabil. 14, 59–68. http://dx.doi.org/10.1310/tsr1403-59.

de Rooij, N.K., Claessen, M.H.G., van der Ham, I.J.M., Post, M.W.M., Visser-Meily, J.M.A., 2017. The Wayfinding Questionnaire: A clinically useful self-report assessment instrument to identify navigation complaints for stroke patients. To appear in Neuropsychological Rehabilitation (in press). http://dx.doi.org/10.1080/09602011.2017.1347098.

Ruggiero, G., Frassinetti, F., Iavarone, A., Iachini, T., 2014. The lost ability to find the way: topographical disorientation after a left brain lesion. Neuropsychology 28, 147–160. http://dx.doi.org/10.1037/neu0000009.

Schmand, B., Lindeboom, J., Van Harskamp, F., 1992. Dutch Adult Reading Test. Swets and Zeitlinger, Lisse, The Netherlands.

Siegel, A.W., White, S.H., 1975. The development of spatial representations of large-scale environments. In: Reese, H.W. (Ed.), Advances in Child Development and Behavior 10. Academic Press, New York, pp. 9–55. http://dx.doi.org/10.1016/S0065-2407(08)60007-5.

Sorita, E., N'Kaoua, B., Larrue, F., Criquillon, J., Simion, A., Sauzéon, H., Mazaux, J.-M., 2013. Do patients with traumatic brain injury learn a route in the same way in real and virtual environments? Disabil. Rehabil. 35 (16), 1371–1379. http://dx.doi.org/10.3109/09638288.2012.738761.

van Veen, H.J., Distler, H.K., Braun, S., Bülthoff, H.H., 1998. Navigating through a virtual city: using virtual reality technology to study human action and perception. Future Gener. Comput. Syst. 14, 231–242. http://dx.doi.org/10.1016/S0167-739X(98)00027-2833aea78.

Wechsler, D., 1997. Wechsler Adult Intelligence Scale—Third edition (WAIS-III). Psychological Corporation, San Antonio, TX.

Wiener, J.M., Büchner, S.J., Hölscher, C., 2009. Taxonomy of human wayfinding tasks: a knowledge-based approach. Spat. Cogn. Comput. 9, 152–165. http://dx.doi.org/10.1080/13875860902906496.

Wilson, B.A., 2002. Towards a comprehensive model of cognitive rehabilitation. Neuropsychol. Rehabil. 12, 97–110. http://dx.doi.org/10.1080/09602010244000020.

Wolbers, T., Hegarty, M., 2010. What determines our navigational abilities? Trends Cogn. Sci. 14 (3), 138–146. http://dx.doi.org/10.1016/j.tics.2010.01.001.

Zhong, J.Y., Kozhevnikov, M., 2016. Relating allocentric and egocentric survey-based representations to the self-reported use of a navigation strategy of egocentric spatial updating. J. Environ. Psychol. 46, 154–175. http://dx.doi.org/10.1016/j.jenvp.2016.04.007.