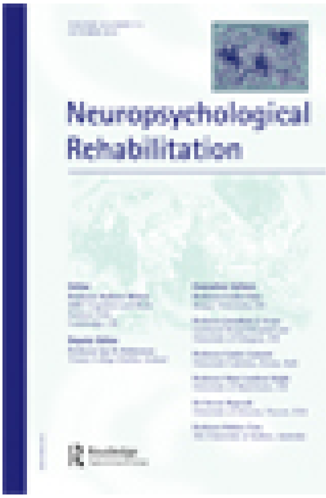

Neuropsychological Rehabilitation: An International Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pnrh20

Navigation strategy training using virtual reality in six chronic stroke patients: A novel and explorative approach to the rehabilitation of navigation impairment

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Published online: 04 Jun 2015.

Neuropsychological Rehabilitation, 2015
http://dx.doi.org/10.1080/09602011.2015.1045910

Navigation strategy training using virtual reality in six chronic stroke patients: A novel and explorative approach to the rehabilitation of navigation impairment

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(*Received 21 August 2014; accepted 21 April 2015*)

Recent studies have shown that navigation impairment is a common complaint after brain injury. Effective training programmes aiming to improve navigation ability in neurological patients are, however, scarce. The few reported programmes are merely focused on recalling specific routes rather than encouraging brain-damaged patients to use an alternative navigation strategy, applicable to any route. Our aim was therefore to investigate the feasibility of a (virtual reality) navigation training as a tool to instruct chronic stroke patients to adopt an alternative navigation strategy. Navigation ability was systematically assessed before the training. The training approach was then determined based on the individual pattern of navigation deficits of each patient. The use of virtual reality in the navigation strategy training in six middle-aged

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The authors wish to thank Merel Braspenning for her help during the study.
No potential conflict of interest was reported by the author(s).
This work was supported by the "Revalidatiefonds" [grant no. R2012090] and by the Netherlands Organisation for Scientific Research (NWO) under a "Meerwaarde" Grant [no. 840.11.006]. Furthermore, IH was supported by NWO under a Veni Grant [no. 451-12-004].

stroke patients was found to be highly feasible. Furthermore, five patients learned to (partially) apply an alternative navigation strategy in the virtual environment, suggesting that navigation strategies are mouldable rather than static. In the evaluation of their training experiences, the patients judged the training as valuable and proposed some suggestions for further improvement. The notion that the navigation strategy people use can be influenced after a short training procedure is a novel finding and initiates a direction for future studies.

Keywords: Navigation strategy training; Virtual reality; Neuropsychological rehabilitation; Stroke patients; Route and survey knowledge.

INTRODUCTION

The ability to find one's way around has been shown to be crucial for adequate and autonomous daily life functioning. When we navigate from one location to another, we rely on multiple cognitive functions and, thus, on the cooperation of different brain structures (Brunsdon, Nickels, & Coltheart, 2007; Wolbers & Hegarty, 2010). The cognitive complexity of navigation behaviour makes this function highly vulnerable to brain damage, as shown in a large number of case studies (e.g., Aradillas, Libon, & Schwartzman, 2011; Ciaramelli, 2008; Ruggiero, Frassinetti, Iavarone, & Iachini, 2014; Van der Ham et al., 2010). The navigation problems of these cases clearly interfere with their adequate and independent daily life functioning. Further evidence for a close relationship between navigation ability and daily life functioning comes from a systematic study in mild stroke patients (Van der Ham, Kant, Postma, & Visser-Meily, 2013). Overall, these studies show a clear need for interventions that aim to improve navigation skills in brain-damaged patients suffering from navigation impairment.

The foremost challenge to overcome in developing an effective navigation training programme is to understand and take into account the substantial cognitive complexity that characterises navigation. Numerous cognitive processes are involved in solving any type of navigational task (Brunsdon et al., 2007; Wiener, Büchner, & Hölscher, 2009; Wolbers & Hegarty, 2010). Information originating from multiple sensory systems is relevant to navigation behaviour, such as from vision, the vestibular system and proprioception (Berthoz & Viaud-Delmon, 1999). Moreover, several cognitive functions, including, but not limited to, spatial processing, (working) memory, mental imagery, attention, and executive functions (e.g., decision-making and planning) interdependently contribute to guide navigation behaviour (e.g., Brunsdon et al., 2007; Guariglia & Pizzamiglio, 2007; Labate, Pazzaglia, & Hegarty, 2014; Wolbers & Hegarty, 2010). A further complexity is that individuals differ considerably in their general spatial abilities as well as in their specific navigation skills (e.g., Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Ishikawa & Montello, 2006). It has even been suggested that such individual differences might not only be related to variables such as gender and age but also partly to personality traits such as neuroticism (Burles et al., 2014).

An extensive range of studies investigated healthy populations in order to unravel the types of environmental representations that humans use and the strategies they employ to approach navigation challenges. Most of these studies support a fundamental distinction of two different mental representations: route and survey knowledge (e.g., Foo, Warren, Duchon, & Tarr, 2005; Latini-Corazzini et al., 2010; Newman et al., 2007; Thorndyke & Hayes-Roth, 1982; Wolbers & Büchel, 2005; Wolbers, Weiller, & Büchel, 2004). Route knowledge contains information about distinctive features in the environment (landmarks), associations between landmarks and directional information (e.g., left turn at the post office), and sequences of landmarks or turns. This type of knowledge is obtained by adopting the perspective of a ground-level observer. Survey knowledge, in contrast, refers to the general layout of the environment from an aerial or map-like perspective. It results in a mental representation of the area, including information about metric distances and angles. This knowledge is typically developed as a result of extensive exploration of an environment or by map learning. The fundamental distinction between route and survey knowledge is helpful in guiding treatment of navigation impairment in brain-injured patients. In our view, however, it is essential also to get hold of the cognitive complexity of navigation and to look beyond this heuristic distinction of the two types of representations and strategies.

Although the number of studies on navigation (as a cognitive ability) has increased over the past decade, a comprehensive theoretical model is still lacking. Nonetheless, this has not prevented us from exploring in this study how currently available knowledge about navigation can benefit the development of a navigation strategy training. Currently, only a limited number of studies has evaluated the effectiveness of navigation rehabilitation programmes (Bouwmeester, Van de Wege, Haaxma, & Snoek, 2015; Brooks et al., 1999; Davis & Coltheart, 1999; Incoccia, Magnotti, Iaria, Piccardi, & Guariglia, 2009; Kober et al., 2013; Rose, Attree, Brooks, & Andrews, 2001). Typically, most of these attempts are characterised by two limitations. First of all, four of these studies are single case reports. More importantly, another shared characteristic of the majority of these navigation training studies is that they focus on learning and recalling a limited set of specific routes. Such an approach has two setbacks: firstly, the tools provided are only applicable for specific navigational tasks (e.g., navigating from home to the supermarket), and secondly, it does not take into account the complex cognitive nature of navigation behaviour. As such, it is unclear whether learning a restricted set of (virtual) routes helps patients to cope with their daily life navigation challenges.

With respect to the tools used in the navigation training, virtual reality (VR) clearly has a number of important advantages over performing exercises in a real environment. VR provides highly realistic and controllable simulations of real-life situations (Rose, Brooks, & Rizzo, 2005) and allows dynamic interplay with the virtual environment. Specifically regarding navigation training for stroke patients, VR provides patients a safe practice environment (without the need to go through busy traffic, etc.) and enables them to practise without delivering any notable physical effort. As fatigue is a common complaint after stroke (Schepers, Visser-Meily, Ketelaar, & Lindeman, 2006), VR facilitates patients to train at a higher intensity than would be possible on the streets. The advantages of VR have already been appreciated by navigation researchers. Its contribution therefore rapidly increased in navigation research (e.g., Ekstrom, Copara, Isham, Wang, & Yonelinas, 2011; Janzen & Van Turennout, 2004; Spiers et al., 2001). Moreover, an increasing number of attempts have also been made to implement this technology in neurorehabilitation training programmes (e.g., Rose et al., 2005; Yip & Man, 2013).

Given the above considerations, we developed a virtual reality (VR) navigation training which aimed to instruct patients to adopt an alternative navigation *strategy*. The content of the training is based on the pattern of navigation deficits of each individual patient. Our expectation is that training patients to use alternative navigation strategies will help to compensate for the navigation difficulties they encounter in daily life. Our approach is unique, as compared to other navigation training studies, in assessing navigation abilities in a very broad sense (including landmark knowledge, sequence of turns, memory for scene order, pointing, etc.). As such, our approach acknowledges the cognitive complexity of navigation behaviour. Furthermore, our focus to instruct patients to use a navigational compensation strategy is novel.

The aim of the current exploratory study is threefold. First of all, we examine the feasibility of the virtual environment as used in this navigation training. Secondly, we evaluate whether or not it is possible for patients to adopt a different navigation strategy in the virtual environment after the training. Lastly, the experiences of the patients with the navigation training programme will be discussed.

METHODS

Participants

Six chronic stroke patients (4 female, 2 male), who participated in a larger study on navigation impairment in stroke patients, were recruited from an existing sample of 77 chronic stroke patients (Claessen, Visser-Meily, Jagersma, Braspenning, & Van der Ham, forthcoming). They lived in the community and were able to move independently. All patients were assessed in their navigation ability by means of a navigation questionnaire and an extensive virtual navigation test battery. Based on the following selection criteria, we contacted eight patients to participate voluntarily in the training: (1) navigation complaints measured as at least one impaired subscale on the self-report Wayfinding Questionnaire (Van der Ham et al., 2013), and (2) at least one impaired navigation subtask score in the Virtual Tübingen test battery. Two of the contacted patients refused, because they were not able to travel multiple times to the rehabilitation centre. The six participating patients confirmed their navigation complaints when they were invited to participate in the training programme. The cut-offs (i.e., below -1.65 *SD* of the mean) for the first and second criteria were determined based on the performance of 60 healthy controls. The controls were highly similar in age ($M = 58.7$, $SD = 9.6$) to the six patients ($M = 57.0$, $SD = 8.9$), as well as in educational level based on Verhage (1964, range: 1–7): patients, $M = 5.7$, $SD = 1.4$, and controls, $M = 5.6$, $SD = 0.9$. The control group comprised 31 females (51.7%) and 29 males (48.3%). A description of the demographic characteristics of the participating patients is provided in Table 1. All training procedures in this study were performed in agreement with the regulations set by local ethical review and the Declaration of Helsinki.

Measures

The scores on the Wayfinding Questionnaire, the neuropsychological screening, and the Virtual Tübingen test battery were used to determine the specific training approach for each individual patient. The ability to adopt the learned alternative navigation strategy after completion of the training was investigated by reassessing a parallel version of the Virtual Tübingen test. The patients were asked to fill out an evaluation form after the training in order to make an inventory of their training experiences. Where available, we report on the daily life effects of the training.

Wayfinding Questionnaire (WQ)

The Wayfinding Questionnaire (Van der Ham et al., 2013) is a Dutch self-report measure of cognitive ability and anxiety regarding navigation in daily life. There were five subscales (response scale: 1–7): navigation (2 items), mental transformation (3 items), distance estimation (4 items), spatial anxiety (8 items), and sense of direction (9 items) (see Appendix A).

TABLE 1
Demographic characteristics of the patients and their scores on the Wayfinding Questionnaire

	Case 1	*Case 2*	*Case 3*	*Case 4*	*Case 5*	*Case 6*
Age (at pre-test)	43	63	53	58	56	69
Gender	Female	Male	Female	Male	Female	Female
Education (1–7)	7	7	6	4	4	6
Diagnosis	Ischaemic stroke	Haemorrhagic stroke	Ischaemic stroke	Ischaemic stroke	Ischaemic stroke	Ischaemic stroke
Affected hemisphere	Right supratentorial	Right supratentorial	Left supratentorial	Bilateral supratentorial	Left supratentorial	Left supratentorial
Date of stroke event	21 October 2009	27 July 2008	8 August 2011	28 March 2009	27 December 2010	28 October 2010
Start of training	24 June 2013	25 October 2013	21 October 2013	5 November 2013	11 November 2013	5 December 2013
Number of sessions	4	3	5	4	4	4
Ratio PE/VR/RL	40/40/20%	50/25/25%	50/50/0%	50/50/0%	50/50/0%	40/40/20%
WQ:						
Navigation	1.5*	3.5	4.0	2.0	3.0	1.5*
Mental transformation	2.0*	3.0	2.3*	3.7	4.0	3.7
Distance estimation	2.8	4.3	2.3	3.0	5.0	2.0*
Spatial anxiety	1.9*	2.0*	2.1*	2.6*	1.5*	2.6*
Sense of direction	2.2	2.6*	2.7*	4.4	5.3	3.0

Higher scores indicate better self-reported navigation ability on the WQ (range: 1–7). The WQ-subscale Spatial Anxiety was reversed, so that a higher score would indicate less spatial anxiety and thus better navigation ability. Impaired scores on the WQ (below −1.65 *SD* of the control group mean) are marked with an asterisk (*). Abbreviations: PE = psycho-education, VR = virtual reality exercises, and RL = real-life exercises.

Neuropsychological screening

To assess relevant neuropsychological impairments, patients were subjected to a short neuropsychological screening pre-training. First, patients performed the Dutch version of the Adult Reading Test (DART, in Dutch: NLV, "*Nederlandse Leestest voor Volwassenen*") to estimate their premorbid intelligence (Schmand, Lindeboom, & Van Harskamp, 1992). The forward and backward versions of the Corsi Block-Tapping Task (Kessels, Van den Berg, Ruis, & Brands, 2008; Kessels, Van Zandvoort, Postma, Kappelle, & De Haan, 2000) were used to measure visuospatial attention and working memory, respectively. Next, the Trail Making Test (Reitan, 1956) was applied to assess psychomotor speed (part A) and divided attention (part B). Lastly, the Digit Span subtest of the Wechsler Adult Intelligence Scale–III (WAIS-III; Wechsler, 1997) served as a measure of verbal attention (forward span) and verbal working memory (backward span). All scores were converted to percentiles based on the accompanying norm groups and scores at or below the 5th percentile were interpreted as "impaired".

Virtual Tübingen test (VT test)

Navigation ability was assessed using the Virtual Tübingen test (Claessen et al., forthcoming; Van der Ham et al., 2010; Van Veen, Distler, Braun, & Bülthoff, 1998), which comprises two phases. In the first learning phase, patients watched a film of a short route through a virtual representation of the German city Tübingen twice and were instructed to pay careful attention to the route. Next, the test phase consisted of 10 tasks (see Appendix B for task descriptions and scoring methods) to assess both route and survey knowledge of the watched route. The first four of these tasks are assumed primarily to tap into aspects of route knowledge, whereas the latter six are regarded as mainly measuring survey knowledge features. As there were two highly comparable routes, patients performed a parallel version in the evaluation session after the training. Both films depicted a route with 11 intersections. At seven of these intersections a left or right turn was taken. At the other four intersections the route continued in a straight-ahead direction. The order of the two films differed between the patients. These two films were only used in the VT test, but not for exercises during the training sessions.

Feasibility and patients' training experiences

Feasibility of the training programme was assessed based on the trainer's observations, for example, with regard to the length of individual training sessions and the user-friendliness of the virtual environment in this patient group. The training experiences of the patients were assessed by way of an evaluation form after completion of the training programme.

Procedure

Pre-training

The VT test was used to assess patients on a range of navigation abilities that are known to underlie successful navigation. The performance pattern on the 10 tasks of the VT test was interpreted by authors MC and IH to establish a profile of strengths and weaknesses within navigation ability for each individual patient. Furthermore, the results on the Wayfinding Questionnaire and the neuropsychological screening were also taken into account to determine the specific training approach for each individual patient.

Training procedure

The default number of training sessions was set to four one-hour sessions. All training sessions were provided by a certified neuropsychologist (author MC). In the first session, psycho-education on navigational strengths and weaknesses was provided to the patient. The trainer and patient tried to relate these findings to the patient's navigation difficulties as experienced in daily life. The trainer also explained the specific, individual approach of the training programme. In the next sessions, patients performed exercises to improve specific navigation skills or learned to change their navigation strategy in general (e.g., from route-based to survey-based). Most exercises were executed using a dynamic version of Virtual Tübingen that could be controlled by means of a joystick. This version allows for two options: free exploration and following specific routes. The rehabilitation centre building (De Hoogstraat Rehabilitation, Utrecht, The Netherlands) and its immediate vicinity were also used for some real-life exercises in three patients (no. 1, 2, and 6). These patients were able to independently walk distances of $\pm$ 1000 metres without getting extremely tired. In between sessions, patients were encouraged to practise the instructed navigational strategy in daily life and describe these experiences in a navigation diary. This "homework" was then discussed and evaluated with the trainer in the next session. Information on the relative contribution of the three elements (psycho-education, including discussion of homework, virtual reality exercises, and real-life exercises) is provided in Table 1 for each patient separately.

For example, for patients with impaired route knowledge (e.g., cases 4 and 5), the training procedure was focused on encouraging them to use a survey-based strategy. Exercises, for instance, addressed the adequate coupling of the ground-perspective with the map view. To do so, patients were provided with a route specified on a map and were then asked to follow this route through the virtual environment. On-screen feedback ("turn around") was provided in case a wrong turn was taken. In another type of exercise, participants had to plan and draw a route on a map and then follow the planned route through Virtual Tübingen. Such an exercise encouraged the patient to prepare a route carefully and adopt a survey-based strategy as well. Most of the sessions included discussing the homework and the completion of two of such exercises in the virtual environment. Further information on the specific exercises used can be found in the case descriptions in the Results section.

Post-training

To evaluate the patients' ability to adopt the instructed navigation strategy in the virtual environment, the VT test was reassessed using a parallel version post-training. They were also asked to fill out a form to evaluate their experiences with the virtual navigation training.

RESULTS

In this section, we first discuss the feasibility of the virtual environment in the navigation training. After that, we briefly describe the pre-training and post-training results (see Tables 1–3) as well as the specific approach that was taken during the navigation training for each patient. Lastly, we evaluate the experiences of the patients with the navigation training.

Feasibility

The feasibility of the virtual environment (Virtual Tübingen) was found to be high in our training programme. All of the six patients learned to control the virtual environment within a single training session, although only patient 2 stated he had some prior experience with virtual reality. Virtual Tübingen was considered fairly realistic by all of the patients. All sessions lasted 60–70 minutes, which was an appropriate duration for five of the six patients. For patient 3, who suffered from fast emergent mental tiredness, pauses had to be built in on a regular basis.

Patients' training results

Case 1

This 43-year-old female reported navigation problems on four WQ subscales (Table 1). The neuropsychological screening showed indications of impaired visuospatial working memory, mental processing speed and divided attention (Table 2), which led the trainer to repeat important information throughout the training and encourage her to focus on only one type of information or task at once. She performed within the normal range on most of the VT tasks except for measures of absolute (Route Progression)

TABLE 2
Patients' scores on the screening of standard neuropsychological tests pre-training

	Case 1	*Case 2*	*Case 3*	*Case 4*	*Case 5*	*Case 6*
DART / NLV						
Est. premorbid IQ	113	128	110	80	91	107
Corsi Task						
Forward product	35 (15th)	35 (15th)	12 (5th)*	40 (30th)	30 (15th)	40 (30th)
Backward product	12 (2nd)*	60 (93rd)	12 (2nd)*	35 (30th)	25 (13th)	24 (18th)
Trail Making Test						
Part A	52 sec. (1st)*	32 sec. (42nd)	44 sec. (5th)*	78 sec. (1st)*	47 sec. (14th)	52 sec. (14th)
Part B	111 sec. (1st)*	102 sec. (12th)	244 sec. (1st)*	211 sec. (1st)*	86 sec. (34th)	105 sec. (21th)
B corrected for A	(8th)	(10th)	(1st)*	(5th)*	(58th)	(38th)
Digit Span (WAIS-III)						
Forward span	8	6	5	5	5	5
Backward span	5	6	4	4	2	3
Correct items	13 (84th)	19 (95th)	14 (40th)	12 (25th)	8 (2nd)*	11 (16th)

Percentiles are displayed between parentheses. All impaired scores ($\leq 5^{th}$ percentile) as compared to accompanying norm groups are marked with an asterisk (*).

TABLE 3
Patients' scores on the Virtual Tübingen navigation task pre-training and post-training

	Case 1		*Case 2*		*Case 3*		*Case 4*		*Case 5*		*Case 6*	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Scene Recognition	86%	68%	64%*	91%	55%*	59%*	59%*	73%	82%	64%*	77%	77%
Route Continuation	73%	45%*	100%	55%	73%	45%*	45%*	45%*	45%*	55%	73%	91%
Route Sequence	100%	57%	100%	57%	43%	29%*	0%*	0%*	14%*	86%	14%*	57%
Route Order	5%*	45%	73%	32%	18%	36%	18%	18%	23%	5%*	23%	32%
Route Progression	67%*	80%	88%	83%	68%*	86%	75%	85%	82%	75%	75%	80%
Route Distance	72%	72%	91%	84%	75%	83%	67%*	85%	74%	66%*	71%	79%
Pointing to Start*	63°	54°	28°	53°	45°	55°	68°	88°*	48°	84°	100°*	43°
Pointing to End*	44°	63°	26°	69°	116°*	112°*	81°	107°*	62°	87°	62°	47°
Map Drawing	0%*	9%	100%	27%	36%	36%	18%	18%	55%	9%	36%	91%
Map Recognition	Correct	Incorrect	Correct	Incorrect	Incorrect	Incorrect	Incorrect	Incorrect	Correct	Correct	Incorrect	Correct

Impaired scores on the Virtual Tübingen test (below −1.65 *SD* of the control group mean) are marked with an asterisk (*). **Scoring: average deviation in degrees; more deviation means less ability.

and relative order (Route Order) (Table 3). The training was focused on instructing her to apply a survey-based strategy (i.e., cognitive mapping) and to plan routes ahead using maps. The latter goal was chosen because she usually felt very uncomfortable while navigating in an unknown environment. During the training, several virtual reality exercises were used to practise pointing ability and facilitate coupling of the ground-perspective with the map view. In the last session, a real-life exercise was performed in which she was asked to plan a route ahead using a map and then follow the chosen route in the real-life environment. Initially, the patient rigidly used only street names to keep track of her current position on the map. However, after a while, she also started to use other types of information for orientation purposes (e.g., the shape of buildings and intersections). In order to practise pointing ability in the real world as well, she was asked to point to the starting point on a regular basis while following the route. In the post-VT test, she had clearly improved on tasks assessing order memory, but this change in focus had a negative effect on performance of five other tasks (Table 3). With regard to daily life effects, the patient noted that she used maps to plan routes ahead on a regular basis and got better at using maps for navigation purposes. Although she felt that her confidence in navigation challenges had increased, she still found it hard to cope with the negative emotions (mostly anxiety) that she experienced when she had problems navigating.

Case 2

The second participant was a 63-year-old male complaining of spatial anxiety and reduced sense of direction (WQ; Table 1). After his stroke, he quit sailing, as he was no longer able to navigate properly on the water in the absence of landmarks. On the streets, he managed to reach his intended destinations, but he regularly noted that he had not taken the shortest route possible. His pre-training VR test performance was fairly accurate; he was only impaired in scene recognition (Table 3). The training aimed to improve his sense of direction by practising pointing tasks in VR and real-life environments (also described as path integration; e.g., Liu, Levy, Barton, & Iaria, 2011; Wolbers, Wiener, Mallot, & Büchel, 2007). In one of the VR exercises, he was given a map of Virtual Tübingen with a specific route indicated. His task was to follow the route in the virtual environment while regularly being asked to point to the starting point of the route. A comparable task was practised in a real-life exercise, in which he was required to follow a route he planned himself. As he was very fast in performing the exercises and mastering the alternative navigation strategy, his training procedure was limited to three sessions. Strikingly, in the post-training assessment, he performed worse on almost all subtasks of the VT test after the training, except for the Scene Recognition task (Table 3). This finding suggests that, due to his focus on remembering scenes and landmarks while watching the route, he might have missed other types of information (e.g., survey knowledge). Although he found the training valuable to gain insight in his navigation abilities, he had expected that his navigation abilities in daily life would have been improved to a larger extent.

Case 3

This 53-year-old female showed impaired scores on three WQ subscales including spatial anxiety (Table 1). The screening suggested impaired visuospatial attention and working memory, reduced mental processing speed and notable difficulties with dividing attention (Table 2). The VT test pre-training revealed evident difficulties in the route knowledge domain (Scene Recognition and Route Progression) as well as in the survey knowledge domain (Pointing to Start) (Table 3). It was decided to focus on the survey strategy, because the ability to recognise landmarks is essential for the route strategy to be effective. It seems difficult to navigate based on remembering landmark–action associations (e.g., "left at the church") or remembering the order of landmarks in case of impaired scene recognition ability. Hence, instructing her to apply a survey-based strategy would reduce the need to rely on scene recognition processes. Due to her attention dividing problems, the purpose of most VR exercises was to teach her to prepare routes using maps beforehand. For example, she had to prepare a route on the map of Virtual Tübingen and was asked to focus on the shape of the route. After that, she used this information in order to follow the planned route in the virtual environment. Given that she suffered from fast emergent mental tiredness, pauses had to be built in. To compensate for these pauses, an additional training session was added to her training programme. Post-training results suggested a clear change in focus on the VR test battery (Table 3). Her performance on two survey knowledge-based tasks was ameliorated (Route Progression and Route Distance), but this had a negative effect on some tasks that primarily rely on route knowledge (Route Continuation and Route Sequence).

Case 4

This 58-year-old male suffering from hemianopia in the right visual field reported spatial anxiety on the WQ (Table 1). The screening revealed reduced mental processing speed as well as difficulties with dividing attention (Table 2). VT test performance particularly indicated route knowledge impairment (Table 3). The approach of the training was comparable to that of the third patient: preparing routes using maps and promoting the survey-based strategy. To do so, he was given multiple exercises to practise pointing ability and coupling of the ground-perspective with the map view. Reassessment of the VR test showed improvement on two survey knowledge-based tasks (Route Progression and Route Distance) as well as better Scene Recognition performance (Table 3). However, there were negative effects on the pointing tasks as well. These results show that he was partly successful in adopting a survey-based strategy.

Case 5

The fifth participant was a 56-year-old female with an impaired spatial anxiety WQ score (Table 1). There were indications of impaired verbal attention and working memory on the neuropsychological screening (Table 2). Pre-training performance on the VR test demonstrated difficulties in the route knowledge domain (Table 3). For this reason, the training was focused at promoting a survey-based strategy. Different types of VR exercises were applied for this purpose: a route preparation exercise, a pointing exercise, and an exercise to practise coupling the ground-perspective with the map view. Although her post-training VR test results seem to point to a general decline in navigation ability, her improvement on the Route Sequence task is remarkable and suggests the opposite (Table 3). The patient was highly accurate in reproducing the overall shape of the route using the printed arrows in this task, suggesting that she constructed a correct mental representation of the route from a survey perspective. In this sense, she was at least partially successful in adopting the survey-based strategy that was being promoted throughout the training. She indicated she was highly content with the training. She found it valuable to have learned to become more aware of the survey aspects of the route as well as knowing how to use maps for navigation purposes. During the training, she applied the newly learned strategy while visiting a city she had not previously been to and reported that it helped her to find her way around.

Case 6

This 69-year-old female reported navigation difficulties on three WQ subscales including spatial anxiety (Table 1). The screening showed no indications of neuropsychological impairments (Table 2). However, she stated she had difficulties with dividing her attention between driving and route following in unfamiliar environments. She never drove an unknown route by car, unless someone showed her the route before. She was impaired on two VT subtasks pre-training: Route Sequence and Pointing to Start (Table 3). Her performance pattern suggested a preference for a route-based strategy guided by landmarks, but sticking to this approach would rather reinforce her to drive only routes that were known to her. To give her confidence in driving in unknown environments, the training focused on instructing her to plan carefully (new) routes ahead by using maps and coupling the ground-level perspective with the map view. Two types of VR exercises were performed for this purpose. In the first type of exercise, the patient was asked to reconstruct a watched route onto the map of Virtual Tübingen. The second type of exercise required her to follow a route in the virtual environment as specified on a map. A real-life exercise was carried out in the fairly complex building of the rehabilitation centre to promote route preparation and coupling the two different perspectives. To this end, she was given a map of the building in which the starting and end points were marked. She had to determine an appropriate route herself and was asked to focus on the route characteristics (e.g., landmarks she would pass along the way). Results of her post-training VR test suggested considerable improvement on all but one subtask of the VT test (Table 3). With regard to navigation on foot, she reported that using maps would now be sufficient to find her way around.

General results

Review of the pre-training and post-training results of the participating patients indicates that one of them (case 6) had clearly improved in navigation ability in general. At least four other cases (i.e., patients 1, 3, 4, and 5) were (in part) successful in adopting an alternative navigation strategy and improved on most of the trained abilities. However, for five of the patients (i.e., patients 1 to 5), there were negative effects on performance of the navigation abilities that were not targeted during the training.

Patients' training experiences and their evaluations

The majority of the patients clearly stated that the training was very valuable and provided more insight into the origin of their difficulties in navigation and/or in learning to adopt an alternative navigation strategy. However, several recommendations were made for improvement of the training. Most of the patients had expected a more extended programme, including a larger number of sessions. It was also suggested that exercises could have been more in depth. Furthermore, one patient noted that the training was focused too narrowly on navigation on foot. Her suggestion was to broaden the focus to navigation by car as well. It was also noted that Virtual Tübingen displays a city without people or vehicles and did not provide an opportunity to exercise while having to cope with interfering cars and distracting noises.

DISCUSSION

In the current study, we conducted a virtual reality navigation strategy training in six chronic stroke patients with navigation difficulties. The focus of the training was to instruct patients to adopt an alternative navigation strategy as a way to compensate for their navigation impairments. Virtual reality was used as an important tool to practise the newly learned navigation strategy in a safe environment (on average 42.5% of the training), in addition to psycho-education and real-life exercises. We will discuss our findings in the light of the three main aims of the study.

Firstly, virtual reality proved to be an appropriate tool for allowing patients to practise the application of a compensatory navigation strategy. Our finding that the use of virtual reality is suitable for rehabilitation purposes accords with earlier navigation training studies (Brooks et al., 1999; Kober et al., 2013; Rose et al., 2001) as well as with rehabilitation studies focusing on other cognitive functions (Rose et al., 2005; Yip & Man, 2013). In addition, sessions lasted approximately 60 minutes, which was found to be appropriate for five of the six patients.

Next, we made comparisons of the pre-training and post-training VT test battery results for each patient individually to evaluate our training. This approach was taken as patients showed highly different performance patterns pre-training. For this reason, we did not conduct analyses on group level performance. We found that one of the cases improved on nine out of the 10 virtual navigation subtasks. Four other cases were also (at least in part) successful in adopting an alternative navigation strategy given their improved performance on most of the trained abilities. However, in five cases, we found that changing the navigation strategy or focus had unexpected negative effects for non-trained abilities or strategies. We assume that patients are limited, most likely due to their brain damage, in their ability to focus broadly on all information from the virtual route. That is, instructing them to focus on a particular type of survey information might result in reduced ability to focus on other types of survey information at the same time. This makes the trainer responsible for finding out what focus will lead to the most beneficial results for each individual patient. These results seem to suggest that the strategy people use to approach navigational challenges can be influenced by a relatively simple and short training procedure.

The above notion that navigation strategies might be mouldable rather than static is important as it encourages further research into navigation *strategy* training programmes. Prior navigation training studies described programmes that focused on patients memorising a limited set of particular routes (Bouwmeester et al., 2015; Brooks et al., 1999; Rose et al., 2001) or street names and their locations (Davis & Coltheart, 1999). As such, these studies trained patients to perform specific navigational tasks (e.g., navigating from home to the railway station) rather than providing them compensatory strategies applicable to any route. As a consequence of this difference in approach, it might well be that our approach places higher demands on the cognitive abilities of the participant. In other areas of neuropsychological rehabilitation, compensatory or strategy training is rather common practice (Cicerone et al., 2011). However, in the context of rehabilitation of navigation impairment, the *strategy* training that we introduced here is a novel approach.

Furthermore, in correspondence with the finding that navigation is a substantial complex cognitive construct (Brunsdon et al., 2007; Wolbers & Hegarty, 2010), we found that all six patients showed different and specific patterns of navigation impairment pre-training. This clearly highlights the importance of individualised interventions to match the specific navigation problems of each individual patient. Our approach of determining the content of the training programme on the pattern of strengths and weaknesses of each individual patient is thus sensible.

It should, however, be noted that the current study design does not yet allow us to draw firm conclusions about the effectiveness of our training procedure. An important limitation of this study is the lack of data on performance on the Virtual Tübingen tests in a control group of non-trained patients. As a consequence, it was not clear whether performance on two successive administrations of the VT would be stable over time in such a group. Including a control group of non-trained patients would allow one to calculate what a reliable change in performance (i.e., the reliable change index; Jacobson & Truax, 1991) is on the different subtasks of the VT test. We therefore recommend that future research evaluating this training approach should incorporate a non-trained control group and apply the reliable change index. Moreover, the current study design does not allow us to establish the relative contribution of the three training components separately (i.e., psycho-education, virtual reality exercises, and real-life exercises).

Lastly, we aimed to evaluate the experiences of the patients with the virtual reality navigation training. Two important recommendations were proposed by the patients for improvement of the training: firstly, a more extensive programme, including a larger number of sessions and exercises and, secondly, a broader focus to take into account navigation by car.

Firstly, in contrast to the patients' recommendation, the objective results of the current study seem to suggest that three to five one-hour training sessions might be sufficient for influencing one's navigation strategy. Extension of the number of training sessions in the presence of the trainer thus does not seem advisable, as it would also lead to an increase of the training costs. Apart from the above conclusion, possibilities for extension of the training could lie in developing additional daily life homework exercises and by adapting the virtual environment such that it would enable practising at home. The current version of VT requires a fairly powerful computer and lacks a convenient and user-friendly interface. Currently, however, the initial results suggest that the present training duration is sufficient. However, whether or not the patients continue to apply the alternative navigation strategy over time is not known.

The second recommendation addresses the fact that the training was primarily focused on navigation on foot. There are two reasons for emphasising this type of navigation in our training. Firstly, navigation on foot is an important mode of transportation in the Netherlands due to the relatively short distances. Navigation by car (or bike) mainly differs from navigation on foot in higher speed of motion and in requiring someone to divide attention between driving and route following. However, this comment also relates to the nature of the used virtual environment in the training. The current version of VT does not display people or vehicles. It might therefore be argued that this limits its generalisability to real-life situations, as there is neither interfering traffic nor distracting noises. Ideally, the virtual environment should include both options so that distractions can be added as the training progresses.

We would like to mention two further recommendations for future studies based on our observations. Firstly, our findings encourage future research to investigate how to gain more control over changing a participant's preferred navigation strategy without affecting the navigation abilities that were intact pre-training. It is also unknown whether these negative effects, when they occur, have an influence on daily life navigation as well. Further research into navigation strategies and how to change them is therefore also desirable in non-clinical groups. In a more general sense, there is a great need for a comprehensive and empirically tested model of navigation as a cognitive function. Such a theoretical model would be helpful in guiding the development of effective and evidence-based training programmes aiming to improve navigation abilities of brain-damaged patients suffering from such difficulties in daily life. On the other hand, waiting for a finalised theoretical model of navigation as a cognitive structure to become available before further investigation of its trainability would be an ineffective approach. We therefore recommend that the two lines of study should run in parallel and, through an interactive approach, their results should affect the direction taken in both.

A useful addition, in order to better evaluate the effects of the navigation training in daily life, would have been the use of goal attainment scaling (GAS; e.g., Bouwens, Van Heugten, & Verhey, 2009). GAS provides a standardised way to evaluate a training programme, such as the navigation training presented here, while taking the goals and needs of the individual patient into account. A limitation of our study is that the daily life effects of the training were addressed in a non-systematic manner.

Lastly, we found that all six patients were impaired on the Spatial Anxiety subscale of the Wayfinding Questionnaire. The participating patients thus tended to experience higher levels of anxiety in the context of navigational tasks as compared to a group of matched healthy controls (see also Lawton, 1994; Van der Ham et al., 2013). The topic of spatial anxiety is relatively unexplored, but the few studies reported have revealed a negative relationship between spatial anxiety and a preference for a survey-based navigation strategy (Lawton, 1994, 1996). More specifically, people who experience lower levels of spatial anxiety tend to rely more strongly on survey knowledge for navigation purposes than people with rather elevated levels of spatial anxiety. As such, it could be argued that the concept of spatial anxiety is highly important to our study, as we encouraged patients to adopt an alternative navigation strategy. We strongly advocate further exploration of the concept of spatial anxiety and its effect on actual navigation performance in both healthy and brain-injured participants.

To conclude, the use of a virtual environment in the context of navigation training was highly feasible in a group of middle-aged stroke patients. In addition, we found initial support for the idea that navigation strategies are mouldable rather than static, even after a relatively short training programme of three to five one-hour sessions. We recommend that the content of interventions aiming to improve people's navigation abilities should fit the specific needs and specific impaired navigation pattern of the individual participant. The current results suggest that teaching brain-damaged patients, who suffer from navigation impairment, to adopt an alternative navigation *strategy* is a sensible approach. Given the limitations of the current study design as discussed above, however, additional investigation of the effectiveness of this approach in a more systematic and controlled study design is certainly necessary.

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APPENDIX A

Wayfinding Questionnaire (26-item version; translated from Dutch)

Navigation

(1) I can effortlessly walk back a route I have never walked before, the same way I walked up.
(2) When I am in a building for the first time, I can easily point to the main entrance of this building.

Mental Transformation

(3) If I see a landmark (building, monument, intersection) multiple times, I know exactly from which side I have seen that landmark before.
(4) In an unknown city I can easily see where I need to go when I read a map on an information board.
(5) While reading a map, I constantly turn the map into the direction that I am going.

Distance Estimation

(6) Without a map, I can estimate the distance of a route I have walked well, when I walk it for the first time.

(7) I can estimate well how long it will take me to walk a route in an unknown city when I see the route on a map (with a legend and scale).
(8) I can always orient myself quickly and correctly when I am in an unknown environment.
(9) I always want to know exactly where I am (meaning, I am always trying to orient myself in an unknown environment).

Spatial Anxiety

(10) I am afraid of losing my way somewhere.
(11) I am afraid of getting lost in an unknown city.
(12) In an unknown city, I prefer to walk in a group rather than by myself.
(13) When I get lost, I get nervous.
(14) How uncomfortable are you in the following situations:
  (a) Deciding where to go when you are just exiting a train, bus, or subway station.
  (b) Finding your way in an unknown building (for example, a hospital).
  (c) Finding your way to a meeting in an unknown city or part of a city.
(15) I find it frightening to go to a destination I have not been before.

Sense of Direction

(16) I can usually recall a new route after I have walked it once.
(17) I am good at estimating distances (for example, from myself to a building I can see).
(18) I can orient myself well.
(19) I am good at understanding and following route descriptions.
(20) I am good at giving route descriptions (meaning, explaining a known route to someone).
(21) When I exit a store, I do not need to orient myself again to determine where I have to go.
(22) I enjoy taking new routes (for example, shortcuts) to known destinations.
(23) I have a good sense of direction.
(24) I can easily find the shortest route to a known destination.

Possible responses ranged from 1 (not at all applicable to me) to 7 (fully applicable to me). Scoring of item 5 and all items of the *Spatial Anxiety* subscale were reversed such that a high score would indicate high self-reported navigation ability. The version that the patients filled out did not include the subheadings.

APPENDIX B

The 10 subtasks of the Virtual Tübingen test battery and their scoring

(1) *Scene Recognition*: Participants had to indicate whether or not 22 individual scenes (11 targets and 11 distractors) were encountered during the route. Scoring: Percentage of correct responses on 22 trials.

(2) *Route Continuation*: Participants were presented with 11 images of decision points and had to indicate in what direction the route continued from each of these decision points. Scoring: Percentage of correct responses on 11 trials.

(3) *Route Sequence*: Participants were asked to replicate the order of the seven turns that were taken during the route by using a set of printed arrows. Scoring: Percentage of correctly indicated left and right turns.

(4) *Route Order*: Participants were required to arrange a set of 11 printed scenes according to the order in which they were encountered during the route. Scoring: Two points were awarded when a scene was assigned to its correct position and one point if it was assigned one position too early or too late. The percentage of obtained points (maximum of 22) was calculated.

(5) *Route Progression*: Participants were shown 11 scenes from the route and asked to indicate the location of each individual scene in the route on a line representing the total distance of the route. Scoring: Percentage of deviation between the indicated and actual position relative to the full length of the line. These scores where averaged over 11 trials.

(6) *Route Distance*: Participants were shown two scenes in each trial (total of nine trials) from the route and had to indicate the distance between these scenes on a line representing the total distance of the route. Scoring: Percentage of deviation between the indicated and actual position relative to the full length of the line. These scores where averaged over nine trials.

(7) *Pointing to Start*: Participants were shown 11 scenes from the route and were asked to point, for each scene, to the start point of the route using a rotational device. Scoring: Deviation in degrees between indicated and correct response averaged over 11 trials.

(8) *Pointing to End*: Participants were shown 11 scenes from the route and were asked to point, for each scene, to the end point of the route using a rotational device. Scoring: Deviation in degrees between indicated and correct response averaged over 11 trials.

(9) *Map Drawing*: Participants were asked to draw the route on a map of Virtual Tübingen. Scoring: Percentage of correctly drawn decision points (11 in total).

(10) *Map Recognition*: Participants were shown four routes on different maps of Virtual Tübingen and were required to indicate which of these depicted the route as seen during the film. Scoring: Correct or incorrect response.