Assessment of Spatial Neglect with a Virtual Wheelchair Navigation Task

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Abstract— **We report data from 9 participants with right hemisphere stroke on a new virtual reality (VR) wheelchair navigation test designed to assess lateralized spatial attention and neglect. The test consists of a virtual winding path along which participants must navigate (or be navigated by an experimenter) as they name objects encountered along the way. There are 4 VR task conditions, obtained by crossing the factors array complexity (Simple, Complex) and Driver (Participant, Experimenter). Participants performed the VR task, a real-life wheelchair navigation task, and a battery of tests assessing arousal, visual attention under secondary task demands, and neglect. The VR test showed sensitivity to both array complexity and driver, with best performance occurring in the Experimenter-Navigated, Simple Array condition. The VR test also showed high correlations with the wheelchair navigation test, and these correlations were in many instances higher than those between traditional clinical neglect tests and the wheelchair navigation task. Moreover, the VR test detected lateralized attention deficits in participants whose performance was within the normal range on other neglect tests. We conclude that the VR task is sensitive to factors likely to affect the severity of neglect in the daily environment, and shows promise as an efficient, easily administered measure of real-life wheelchair navigation.**

I. INTRODUCTION

HEMISPATIAL neglect is a failure to attend to or orient toward the side of space opposite a brain lesion. It is a common consequence of right hemisphere stroke, occurring in approximately 50% of acute patients, and persisting into the chronic stage in at least mild form (i.e., as indicated by below-cutoff performance on at least 1 clinical test) in approximately 75% of those patients [3, 8]. Neglect contributes significantly to the disability resulting from stroke. Patients with neglect are more impaired than patients without neglect on measures of impairment and disability [14], have poorer motor function than patients without neglect, and after hospital discharge are rated as more burdensome to family members, even after controlling for FIM score [3].

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Neglect is frequently assessed with paper-and-pencil tests requiring patients to respond to stimuli in left and right hemispace (e.g., [25]). For example, patients may be asked to cross out all of the letters on a page, or denote the center of a line. These tests are usually amply sensitive for detecting moderate to severe neglect, but may fail to detect more subtle (but still clinically important) deficits. There is also evidence that neglect may be more severe and/or frequent in the clinical setting than typically reported on the basis of paper-and-pencil tasks. In a recent large-scale study of right hemisphere stroke patients [3], we asked physical and occupational therapists to respond to a questionnaire to denote whether they thought neglect was present in such clinical activities as route-finding, ambulation, and activities of daily living (ADLs), and compared these ratings to classifications derived from paper-and-pencil neglect tests. For 13 of the 15 cases in which there was disagreement between therapists and paper-and-pencil classification (87%), subjects were more likely to be classified as having neglect by therapists than by paper-and-pencil tests.

Consistent with the possibility that neglect symptoms are more likely to be revealed in complex tasks (such as daily activities and ambulation) that require considerable attentional resources, performance of a secondary task with non-lateralized general attentional requirements has been shown to worsen performance on neglect tests [17, 18]. Conversely, cueing neglect patients with a tone or command to "wake up!" reduces the severity of neglect [19]. These data suggest that test measures having a strong attentional component may be optimally sensitive to neglect. In addition, density of visual information affects visual search in healthy subjects [1, 6, 20], and may be a strong predictor of the severity of neglect [12, 13].

Despite the importance of assessing the ability of neglect patients to navigate in naturalistic environments, there are few standardized measures of this skill. A recent literature search revealed only one: an obstacle-course measure of wheelchair mobility in which collisions and sideswipes are tallied [21-23]. Importantly, the obstacle-course measure accurately predicts frequency of patient falls. Among the likely reasons for the dearth of such measures is that such tasks require considerable set-up time, large amounts of testing space, and the ability to standardize the course and the locations of obstacles. These are practical shortcomings that are avoided in virtual reality (VR) tasks.

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Although there is some encouraging new work focusing on the use of VR as a rehabilitation assessment and treatment tool in patients with stroke and traumatic brain injury, to our knowledge peer-reviewed experimental studies on the VR assessment or treatment of neglect number fewer than five. One of the first of such studies used a head-mounted display (HMD) system with intrinsic eye-tracker to present 2 scenes (a clock and a group of virtual objects) to 2 patients with neglect [11]. The investigators concluded that the VR system detected neglect, as evidenced by reduced scanning of the contralesional scene, as well as reduced report of objects on the contralesional side. Additionally, they claimed that as compared to traditional paper-and-pencil tests, the VR system was superior in assessing the severity of neglect, but supporting data were not provided. Another recent VR study of neglect assessed 4 neglect patients and 2 patients without neglect on a street-crossing task presented on a 15-inch computer monitor [24]. The patients' task was to navigate an avatar (in this case, the image of the back of a person) across a busy street, using the keyboard arrow keys to control turning of the avatar's head to the left and right. Dependent measures were time taken to complete 7 levels of the task, checking for traffic, and collisions of virtual vehicles with the avatar. The investigators claimed that the non-neglect patients differed from the neglect patients in these measures, but no statistical analyses were performed. (But see [15]).

In the study to be described here, we had three major aims. Our first aim was to develop and pilot a brief test of virtual wheelchair navigation that correlates with a real-life measure of wheelchair navigation, and correlates at least as strongly with real-life wheelchair navigation as do paper-and-pencil tests. Given evidence that neglect may be more severe when attentional demands are high and/or when visual arrays are complex, our second aim was to assess the prediction that neglect in the VR task would be more severe a) when patients navigate actively via joystick, rather than being conveyed passively through the virtual environment by an examiner, and b) when the virtual environment is dense rather than sparse. Finally, based on evidence that neglect of personal, peripersonal, and extrapersonal space may dissociate, our third aim was to assess the relationship of performance on the VR task to performance on measures of these subtypes of neglect.

II. METHOD

A. Subjects

Nine right hemisphere post-acute stroke patients participated in the study. The sample consisted of seven males and two females (avg. age=57.3, SD=14.6; years of education =14.2, SD=2.7; avg months post CVA=31.9, SD=23.1). All participants were paid for their participation and gave informed consent in accordance with the IRB policies of Albert Einstein Healthcare Network and Magee Rehabilitation Hospital.

B. Test Protocol

Virtual Wheelchair Navigation Test (VWNT):

The hardware for the VR task consisted of a motorized wheelchair operated by joystick, a wheelchair treadmill that interfaces through a digital encoder device to a Pentium R 4

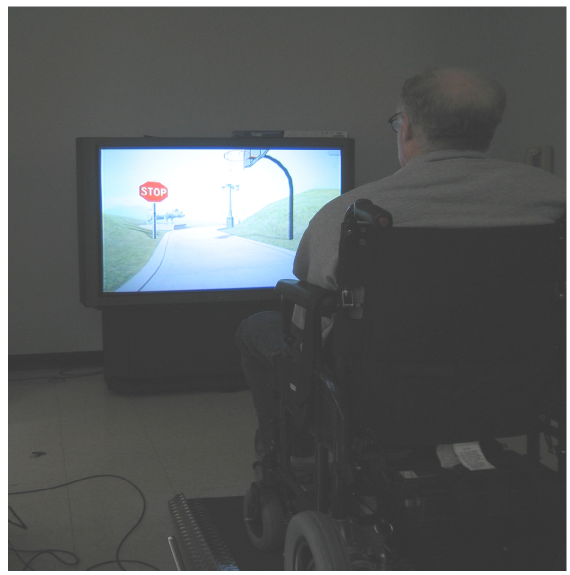


Fig. 1. Photograph of a subject using the wheelchair treadmill apparatus.

CPU 2.4 Ghz PC with a 74.5 GB HD and 512 MB RAM, a 3Dforce 4 Ti4600 NVIDIA Video card, and a 42 by 31 inch flat-screen display (See Figure 1). The VR software design was conceived by members of our research team and programmed by Digital Mediaworks. The participants' navigated the motorized wheelchair via a joystick or were conveyed passively by the experimenter along a virtual non-branching path, with virtual outdoor objects (e.g., colored trees, statues of animals, and other objects) appearing on the left and right of the path. Participants were asked to name all of the objects seen as precisely as possible (e.g., red tree, horse statue), to avoid bumping into any objects, and to complete the course as quickly as possible. When an object was contacted, there was a collision noise, and the wheelchair stopped until the participant resumed navigation.

There were two levels of array complexity. At the simple level, the array contained 10 objects on each side of the path (n = 20 objects total), and all of the objects were trees of various common colors (e.g., red, blue, yellow) and statues of common animals (e.g., cow, dog, cat). At the complex level, the array contained 10 common outdoor objects on each side of the path (e.g., benches, fountains, bushes, phone booths, etc) in *addition* to the same trees and statues present at the simple level (n = 40 objects total) (see Figure 2). Subjects were asked to name all objects.

There were two levels of subject activity that were crossed with the 2 levels of array complexity, for a total of 4 conditions. In the Participant-navigated conditions, the subject operated the motorized wheelchair him or herself with a joystick. In the Examiner-navigated condition, the wheelchair was conveyed along the center of the virtual path at a constant rate, the slowest at which the apparatus operates, by the experimenter operating a joystick. The course was traversed 2 times in each condition, once "coming" and once "going", so that particular objects were viewed once on the left and once on the right in each condition, thus controlling for possible item-specific differences in difficulty of object perception or naming. The order of the four conditions was counterbalanced across subjects.

All testing was performed in dedicated testing space at Magee Rehabilitation Hospital. Performance was assessed by 1) An Object Naming Score for objects named on the left, 2) in the Participant-navigated conditions, number of objects collided with on the left. The Object Naming Score was calculated as follows: Complete identification including unique attributes (e.g., horse statue, red tree) = 3 points; category or color error (e.g., horse statue → cow statue, red tree → pink tree) = 2 points; vague description (e.g., *Moss-Magee Wheelchair Navigation Test (MMWNT):*

This test is a modification of a published wheelchair navigation task [22, 23]. Participants who had not first performed the VR task (see counterbalancing, below) received training and practice in the use of a motorized wheelchair, sufficient to perform independently. They were then asked to twice complete a course (once backward, once forward) of 150 feet long X 5 feet wide demarcated by rope, requiring 3 right and 3 left turns, with 6 obstacles (folding chairs) located on each side. Performance was videotaped, and contacts with the obstacles on each side were scored on-line and checked against the videotapes. The published version of this test has demonstrated inter-rater reliability of .96 for hits and .90 for sideswipes. Five of the subjects performed the VR assessment first, and the other 4 subjects first performed the MMNT and visual attention tests to be described next.

Neglect and Attention Battery:

1. Visual fields and extinction were assessed with presentation of 4 unilateral left, 4 unilateral right, and 4 bilateral stimuli in upper, middle, and lower hemifields (36 trials total) in random order. Participants who reported less than 4 unilateral left stimuli in any sector were characterized as exhibiting a visual field defect. Patients who reported 3 or 4 unilateral left stimuli, and who reported at least one fewer left stimuli on bilateral trials, were characterized as exhibiting extinction. Note that there is no consensus for a particular cut-off score defining extinction, as it is likely to be a continuous rather than discrete phenomenon. A recent review [7] presents data from patients whose extinction ranges from 15% to 80%

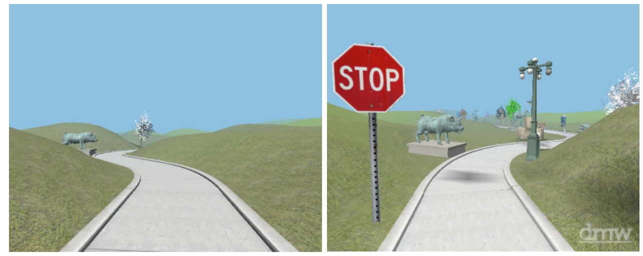


Fig. 2. Screen shots from the Simple (left) and Complex (right) Array conditions of the VWNT.

of left sided targets on bilateral trials depending on stimulus characteristics.

2. Standard Paper and Pencil Neglect assessment measures included subtests from the Behavioural Inattention Test (e.g., Letter Cancellation, Line Bisection, Picture Scanning and Menu Reading) [25] and the Bell Cancellation Test [9].

3. The Dual Task test is a computerized measure of simple response time with and without a secondary task load [16]. In the baseline condition (DT Base), subjects responded with a keypress to 64 black circles 1cm in diameter appearing in randomized locations on a computer screen at intervals of 500-2000 msecs over 64 trials. In the dual task condition (DT Dual), subjects performed the DT Base task in conjunction with an oral digit repetition task conducted at span. Interference associated with the secondary task was measured by subtracting the mean response latencies on DT Base from DT Dual (DT Decrement). Decrements in response to contralesional targets under Dual Task load was measured by subtracting mean response latencies to left targets in DT Base from DT Dual (L Dual- L Base).

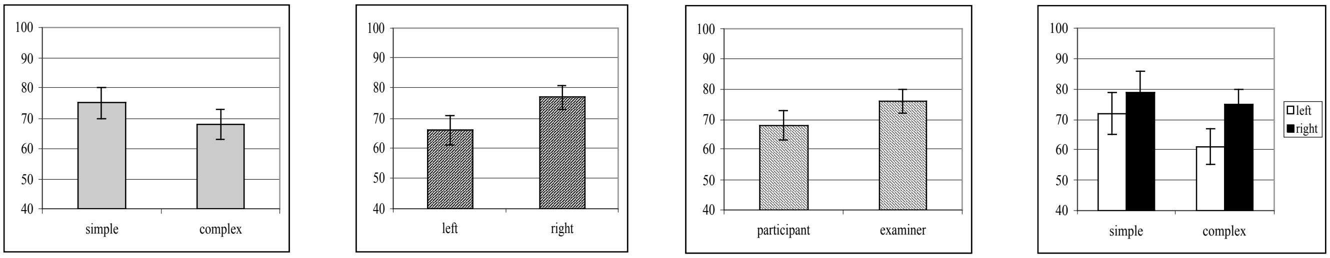
4. Personal neglect was assessed with the "Fluff" test, administered by placing six cotton balls on a blindfolded participant's left side at shoulder, chest, elbow, forearm, wrist, and hip (for a similar test see [4]). Upon removal of the blindfold, the participant was instructed to locate and remove the cotton balls. The number of detected targets was tallied (0-6). Extensive data are available on the performance of right hemisphere stroke patients on this measure from our previous research [3].

5. Extrapersonal neglect was measured with a test modified from a previously published measure [2, 10]. Participants were asked to denote the center of 3 long (6" – 3') lines presented on poster paper on a wall 4 feet from them by means of a laser pointer. There were 4 trials with each line length, presented in random order, for a total of 12 trials. Mean deviation from the true center in the line was measured on this task.

III. Results

A. Virtual Reality Task.

A repeated measures ANOVA was performed on the Object Naming Score of all participants with Driver (Participant, Examiner), Array Complexity (Simple, Complex), and Array Side (Left, Right) as within-subjects factors. Figure 3 shows all significant and trend effects. There were main effects of Array Complexity, $F(1,8) = 11.9$, $p < .01$, and Array Side,



3a 3b 3c 3d

Fig. 3a-d. All significant and trend-level ANOVA effects (left sided total % correct) from VWNT. 3a: Driver main effect. 3b: Array Side main effect 3c: Array Complexity main effect. 3d: Array Side X Complexity interaction.

$F(1,8) = 5.5$, $p < .05$, and a trend toward an effect of Driver, $F(1,8) = 3.5$, $p = .09$. Participants achieved lower scores in the Complex Array than Simple Array conditions, and lower scores for Left than Right targets. There was also a trend toward an interaction of Array and Side, $F(1,8) = 2.4$, $p = 0.1$. Post-hoc testing of the Array Complexity X Array Side effect with Bonferroni-corrected 2-tailed t-tests ($p < .012$ required for significance) revealed a reliable difference between Left and Right scores in the Complex ($p =.005$) but not Simple ($p = .07$) arrays. Moreover, scores on the Left were worse in the Complex than Simple Array ($p = .006$), whereas scores on the Right were not reliably affected by Array Complexity ($p = .19$). Four of the subjects collided with at least one object. There were more collisions with left-sided than right-sided virtual objects, though the difference was not significant (Left mn. = .28, s.d.= 5.7, range = 0-23; Right mn. = .11, s.d. = .22, range = 0-1; $t(8) = 1.2$, $p = .28$). One participant (s9) showed a striking left vs. right difference in number of virtual collisions (Left = 35, Right = 1).

To obtain a preliminary assessment of the sensitivity of the VR task to mild attentional deficits, we examined the VR performance of the 3 mildest patients (as judged by an average score from the Bell Test and Letter Cancellation Test). These 3 subjects had difficulty with the VR task, despite performance well within the range of healthy controls on the Bell Test [9] and letter cancellation test [25].

B. Moss-Magee Wheelchair Navigation Test (MMWNT); Neglect and Attention Battery.

Correlations between participants' MMWNT, the standard neglect/attention test battery and the metrics from the VR task are shown in Table 1. It can be seen that there are strong correlations between the VR tasks and the other tasks. Of particular interest is the strong correlation of the MMWNT and mean VR score ($r = -0.85$). Although caution should be used in interpreting differences in the strength of correlations obtained with such a small sample, it is encouraging to note that the correlation the MMWNT and VR score surpasses

those observed between the MMWNT and the traditional paper-and-pencil tests (Bell, Letter, Line Bisection, Picture, and Menu), which ranged from $r = -0.75$ to $r = -0.77$, and is similar to the correlations seen between the MMWNT and the laser test for extrapersonal neglect ($r = 0.84$), and between the MMWNT and the computerized dual task measures ($r = 0.82$, $r = 0.88$). Correlations between the VR scores and the "Fluff" test were quite weak, and between the VR scores and laser test were also somewhat weak, suggesting the possibility that the VR task may more accurately measure peripersonal neglect than either personal or extrapersonal neglect.

IV. Conclusions

We have provided encouraging data from a small sample of right hemisphere stroke patients on a new virtual reality assessment tool for measuring wheelchair navigation abilities. The VR wheelchair navigation task we developed is considerably more feasible to administer than real-life wheelchair navigation tests, and the VR task and a measure of wheelchair navigation (the MMWNT) tests correlate more strongly than do paper-and-pencil neglect tests and the MMWNT. The observed correlations are particularly encouraging given the small sample size. Thus, the VR wheelchair navigation test shows promise as a predictor of navigation safety. Additionally, the VR task demonstrated sensitivity to mild neglect in patients whose performance on paper-and-pencil tests was in the normal range. This suggests that the VR task may also evidence incremental validity for detecting neglect in mild patients.

Moreover, the VR task demonstrated sensitivity to two factors that are likely to have considerable clinical relevance for neglect patients. First, the VR task is sensitive to the effect of the density of the visual array. Patients reported significantly fewer objects in the complex arrays compared to the simple arrays, and there was a tendency for the complexity effect to be more pronounced for left-sided than right-sided objects. This is commensurate with a number of investigations in healthy subjects [1, 5, 20] and patients with neglect [12, 13] indicating that visual search is more time-consuming and less accurate in dense than sparse visual arrays. MATH

Second, as judged by the tendency toward better performance when examiner-navigated as compared to self-navigated, the VR task is sensitive to the requirement to divide attention between two tasks (in this case, navigation and object naming). This is consistent with the literature suggesting that general (non-lateralized) attentional deficits are a factor in the severity of neglect [17, 18]. Importantly, individual patient profiles on the VR task indicate that not all patients are equally sensitive to the effects of array density or divided attention. The VR wheelchair navigation task may thus be useful in targeting patients likely to benefit from particular rehabilitation strategies. For example, patients exhibiting adverse effects of divided attention may prove responsive to interventions aimed at generalized attention and arousal deficits (e.g., alerting therapies [19]). Also, based on the considerable ($r = -0.94$) correlation between collisions on the MMWNT and object

TABLE I
CORRELATION COEFFICIENTS FOR NEGLECT TESTS, VR TASK, AND MMWNT

	VR Task					
Neglect Tests	Participant-driven, Simple Array	Participant-driven, Complex Array	Examiner Driven, Simple Array	Examiner Driven, Complex Array	Mn. VR Score	MMWNT
Bell Test	**0.83**	**0.85**	**0.82**	**0.86**	**0.87**	-0.76
Letter Cancel.	**0.91**	**0.95**	**0.91**	**0.92**	**0.95**	-0.77
Line bisection	**-0.86**	**-0.84**	**-0.86**	**-0.80**	**-0.87**	-0.75
Picture	**0.91**	**0.89**	**0.93**	**0.78**	**0.91**	-0.77
Menu	**0.92**	**0.90**	**0.79**	**0.88**	**0.91**	-0.75
Fluff Test	0.33	0.30	0.09	0.25	0.23	-0.71
Laser Line Bisection	-0.66	-0.66	-0.48	-0.63	-0.63	**0.84**
Dual Task Base, L	**-0.99**	**-0.96**	**-0.94**	**-0.87**	**-0.97**	**0.88**
Dual Task Dual, L	**-0.96**	**-0.92**	**-0.86**	**-0.84**	**-0.93**	**0.82**
Dual Task Interferenc	**0.87**	**0.82**	0.72	**0.76**	**0.82**	0.72
MMWNT	**-0.94**	-0.72	-0.69	-0.79	**-0.85**	

***p < .01**

naming in the Participant-navigated, Simple array condition of the VR task, it may not be necessary to administer all 4 VR conditions to predict real-life wheelchair navigation ability. Additional testing with a larger sample of patients will be required to confirm this possibility.

There were also strong correlations of the Laser Line Bisection Test and the MMWNT and the Dual Task measures and the MMWNT. Given that these tests correlate so well with the MMWNT, one could argue that these tasks, rather than the VR task, might be usefully developed to predict wheelchair navigation. One clear advantage of the VR task is that it is a transparent measure of wheelchair navigation, and thus may be more easily interpreted by clinicians, and more useful in educating patients and caregivers. Other advantages, noted earlier, include the VR task's sensitivity to array complexity and divided attention.

One obvious disadvantage is that, in its present form, the VR task requires specialized hardware (the wheelchair treadmill). In the future, development of an analogous VR wheelchair navigation task not requiring this apparatus may prove useful. Additional directions for development include further increasing the array complexity with additional and/or moving objects, presumably thereby further increasing the test sensitivity. Finally, attentional processing demands (and verisimilitude) could be increased with the addition of a soundtrack of realistic environmental sounds.

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