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Neurorehabil Neural Repair 2012 26: 120 originally published online 11 July 2011
DOI: 10.1177/1545968311410068

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What is This?
Mapping the Neglected Space: Gradients of Detection Revealed by Virtual Reality

Assaf Y. Dvorkin, PhD1,2, Ross A. Bogey, DO1,2, Richard L. Harvey, MD1,2, and James L. Patton, PhD1,2,3

Abstract

Background. Spatial neglect affects perception along different dimensions. However, there is limited availability of 3-dimensional (3D) methods that fully map out a patient’s volume of deficit, although this could guide clinical management. Objective. To test whether patients with neglect exhibit simple contralesional versus complex perceptual deficits and whether deficits are best described using Cartesian (rectangular) or polar coordinates. Methods. Seventeen right-hemisphere persons with stroke (8 with a history of neglect) and 9 healthy controls were exposed to a 3D virtual environment. Targets placed in a dense array appeared one at a time in various locations. Results. When tested using rectangular array of targets, subjects in the neglect group exhibited complex asymmetries across several dimensions in both reaction time and target detection rates. Paper-and-pencil tests only detected neglect in 4 of 8 of these patients. When tested using polar array of targets, 2 patients who initially appeared to perform poorly in both left and near space only showed a simple left-side asymmetry that depended almost entirely on the angle from the sagittal plane. A third patient exhibited left neglect irrespective of the arrangements of targets used. An idealized model with pure dependence on the polar angle demonstrated how such deficits could be misconstrued as near neglect if one uses a rectangular array. Conclusions. Such deficits may be poorly detected by paper-and-pencil tests and even by computerized tests that use regular screens. Assessments that incorporate 3D arrangements of targets enable precise mapping of deficient areas and detect subtle forms of neglect whose identification may be relevant to treatment strategies.

Keywords

neglect, virtual reality, spatial dimensions, perceptual deficits

Introduction

Spatial neglect is a common and disabling deficit following stroke, particularly prominent after right-hemisphere lesions.1 Patients with neglect often fail to detect, attend, or respond to stimuli and events occurring in selective parts of space, typically the contralesional side.2 From a clinical perspective neglect represents an important disorder as it has proven to be a negative prognostic factor, associated with poorer functional outcome and duration of rehabilitation.3-5

Whereas earlier studies viewed neglect as a unitary condition,6 recent evidence indicates that neglect comprises a heterogeneous, multifaceted set of behavioral symptoms.7-10 A particularly important example of this heterogeneity is the variability of spatial representation. Early studies reported deficits in terms of a left–right (horizontal) dichotomy. In the past 2 decades, studies began reporting neglect along different spatial dimensions—horizontal, radial (near–far space), and vertical.11-19 These studies, however, investigated only one or more independent dimensions, using mostly line bisection and cancellation tasks. Although widely used, these tasks allow limited quantification of performance in different spatial locations and do not reflect the reality of a 3-dimensional (3D) world. A recent study that used a rather dense computerized 2D array of targets has concluded that providing quantitative information on patients’ performance in (at least) 2 dimensions is essential for accurate assessment of neglect.20

Despite extensive research, no consensus exists for a gold standard method of assessing neglect. Over the years, studies adopted various methods, commonly using paper-and-pencil tests (eg, Behavioral Inattention Test [BIT]).21 Although these tests can be administered quickly...
and easily, they have several drawbacks, which often leads to a misdiagnosis of less severe cases. The reported frequency of neglect varied widely (13% to 82%) for right brain-damaged patients. It has been suggested that assessment methods were one of the main factors explaining the discrepancies between the studies.

Technological advancements have made it feasible to develop and administer computerized assessments of neglect. Virtual reality (VR), a computer-generated environment that displays objects in 3D space, has been effectively used to study cognitive and motor functions in healthy subjects and various patient populations such as stroke. VR offers better control over stimulus presentation and timing. The advantage of VR over regular 2D screens is the incorporation of depth dimension. In fact, previous studies have identified different mechanisms for coding different space representations.

Although a growing number of studies use VR for assessment and rehabilitation of persons with stroke, there have been relatively few published studies on VR applications for assessment and treatment of neglect. Although the majority of these studies demonstrated the feasibility of VR for detecting neglect, they did not examine fundamental characteristics of perceptual neglect in 3D space. That is, they did not use all 3 dimensions for stimuli presentation. We have recently reported preliminary observations with a history of spatial neglect (N+) were tested. As left inattention can result from visual defects, gaze preference (related to lesion site), or neglect, behavioral observations and provocative examinations were used to tease out neglect. In addition, 9 persons with right-hemisphere stroke with no history of spatial neglect (N−) and 9agematched healthy controls (HC) were tested. Subjects were right-handed by self-report. Personal and clinical details of the 3 subject groups are shown in Table 1. A one-way analysis of variance (ANOVA) confirmed that there was no significant difference between the mean ages for the 3 groups, $F(2, 23) = 0.47, P = .63$. All procedures were approved by the Institutional Review Board of Northwestern University.

**Apparatus and Data Collection.** The VRROOM (Virtual Reality and Robotics Optical Operations Machine) system was used for this study (Figure 1A). A cinema-quality digital projector (Christie Mirage 3000 DLP, Christie Digital Systems, Cypress, California) displayed the images over a 5-foot-wide 1280 × 1024 pixel image resulting in a 110° wide viewing angle. A tracking sensor (Ascension Technology, Burlington, Vermont) attached to stereo shutter glasses worn by the subject (StereoGraphics Inc, San Rafael, California) was used for tracking head motion. The immersive environment consisted of a 3D room shape with a simple background texture (presenting enough cues for depth perception). Targets (generated as 3D virtual ball-shaped targets with a 1.5 cm radius) appeared at various locations within the 3D space (Figure 1B). Subjects sat in a dark room on a chair placed in front of the system, holding a response button in their right (unimpaired) arm. A chin rest kept the head position constant.

**Procedures.** Prior to beginning of the testing, subjects completed the 6 paper-and-pencil subtests of the conventional BIT (line crossing, letter cancellation, star cancellation, figure copying, line bisection, and representational drawing; with cut-off of 129). Total BIT scores are presented in Table 1.

In Experiment 1 there were 105 possible targets, distributed on a $7 \times 5 \times 3$ (horizontal × radial × vertical) Cartesian grid (Figure 1B). Targets were distributed from right to left of body midline, above, below, and at eye level, and in near (peripersonal) and far (extrapersonal) space relative to the subject’s body. Note that targets were static. On each trial, only one target (of the 105) appeared randomly in space. Overall, each target appeared 8 times. Subjects were instructed to press a response button as fast as they could whenever they detected a target. Each trial began with the appearance of a fixation cross (at the center of the scene, aligned with body midline, at eye level) for a time interval ranging from 0.5 to 1 second. A visual target appeared simultaneously with the disappearance of the fixation cross, and remained visible until the button was pressed or as 3 seconds elapsed. Fixation was not required for the entire trial. The next trial began after a 1.5-second interval. To...
discourage anticipatory responses, occasional catch trials were included where no target appeared, and subjects were required to withhold button press. The experiment was divided into blocks of trials (total of 936 trials). Subjects could rest between blocks.

Data Analysis. Reaction time (RT) to initiate a button press and the percentage of correct detection of visual targets were calculated offline, separately for each of the 105 targets. Less than 0.5% of trials were excluded from the analysis because of small RT (<180 ms) for both patients and healthy controls. False-alarm responses (ie, button press on catch trials) occurred rarely (2% of catch trials). One-way ANOVAs with target location as a within-subject factor were performed separately for each spatial dimension. The significance level was set at .05. Post hoc analyses were conducted using Bonferroni tests.

Results

Results indicated clear differences among all subject groups. Whereas performance on the VR task indicated an obvious spatial neglect for all patients in the neglect group, performance on the BIT (subtests and total scores) indicated the presence of neglect in only 4 of 8 of these patients (see Table 1). Neglect patients who scored above the BIT cut-off level still exhibited perceptual deficits on the VR task and differed significantly from controls (HC and N−).

Mean RT and percentage of correct detection, calculated for each subject, showed obvious variations across space only for patients in the neglect group. A 3D view of the calculated mean RT and percentage of correct detection are depicted in Figures 1C and 1D, respectively. Representative examples for a healthy subject (left panels) and a neglect patient (right panels) are shown. To better illustrate the observed variations across different dimensions, Figure 2 collapses the results to single dimensions (left, middle, and right panels, respectively), for both RT and correct detection (Figures 2A and 2B). Subjects from the control groups detected all targets, irrespective of target location. The mean RT (±SD), across all target locations, was 541 ± 65 ms for healthy controls and 627 ± 96 ms for control patients. Whereas control patients exhibited significantly longer RT compared with healthy controls, F(1, 1888) = 523, P < .0001, subjects from both groups initiated a button press evenly across all targets in all 3 dimensions. In contrast, all patients from the neglect group exhibited variations of RT and correct detection, exhibiting complex asymmetries across several dimensions. Furthermore, their mean RT for all target positions was

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age, y</th>
<th>Education, y</th>
<th>Lesion Site</th>
<th>Etiology</th>
<th>Months Since Onset</th>
<th>Visual Field Deficit</th>
<th>BIT Total Score</th>
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<tbody>
<tr>
<td>N+ 1</td>
<td>M</td>
<td>60</td>
<td>16</td>
<td>T, P, BG</td>
<td>H</td>
<td>6</td>
<td>137</td>
</tr>
<tr>
<td>N+ 2</td>
<td>F</td>
<td>38</td>
<td>16</td>
<td>T, P, BG</td>
<td>H</td>
<td>36</td>
<td>136</td>
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<tr>
<td>N+ 3</td>
<td>M</td>
<td>52</td>
<td>15</td>
<td>MCA</td>
<td>I</td>
<td>57</td>
<td>141</td>
</tr>
<tr>
<td>N+ 4</td>
<td>F</td>
<td>52</td>
<td>12</td>
<td>F</td>
<td>H</td>
<td>33</td>
<td>141</td>
</tr>
<tr>
<td>N+ 5</td>
<td>M</td>
<td>55</td>
<td>16</td>
<td>Th</td>
<td>H</td>
<td>1</td>
<td>142</td>
</tr>
<tr>
<td>N+ 6</td>
<td>F</td>
<td>70</td>
<td>13</td>
<td>MCA</td>
<td>I</td>
<td>12</td>
<td>Unknown</td>
</tr>
<tr>
<td>N+ 7</td>
<td>F</td>
<td>73</td>
<td>15</td>
<td>T, P, BG</td>
<td>I</td>
<td>3</td>
<td>140</td>
</tr>
<tr>
<td>N+ 8</td>
<td>M</td>
<td>72</td>
<td>14</td>
<td>T</td>
<td>H</td>
<td>1</td>
<td>123</td>
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<td>M</td>
<td>52</td>
<td>13</td>
<td>Ic, Pu, Cl</td>
<td>I</td>
<td>135</td>
<td>No</td>
</tr>
<tr>
<td>N− 2</td>
<td>M</td>
<td>61</td>
<td>12</td>
<td>P, F</td>
<td>H</td>
<td>70</td>
<td>No</td>
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<tr>
<td>N− 3</td>
<td>M</td>
<td>60</td>
<td>16</td>
<td>F, BG, Cr, Ic</td>
<td>I</td>
<td>53</td>
<td>No</td>
</tr>
<tr>
<td>N− 4</td>
<td>M</td>
<td>65</td>
<td>13</td>
<td>Th</td>
<td>H</td>
<td>72</td>
<td>No</td>
</tr>
<tr>
<td>N− 5</td>
<td>M</td>
<td>48</td>
<td>16</td>
<td>MCA</td>
<td>H</td>
<td>11</td>
<td>No</td>
</tr>
<tr>
<td>N− 6</td>
<td>M</td>
<td>73</td>
<td>12</td>
<td>T, motor and premotor area</td>
<td>H</td>
<td>120</td>
<td>No</td>
</tr>
<tr>
<td>N− 7</td>
<td>M</td>
<td>53</td>
<td>22</td>
<td>F, P</td>
<td>I</td>
<td>19</td>
<td>No</td>
</tr>
<tr>
<td>N− 8</td>
<td>F</td>
<td>62</td>
<td>12</td>
<td>BG, InC</td>
<td>I</td>
<td>49</td>
<td>No</td>
</tr>
<tr>
<td>N− 9</td>
<td>M</td>
<td>63</td>
<td>20</td>
<td>Carotid artery</td>
<td>I</td>
<td>48</td>
<td>No</td>
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<tr>
<td>HC</td>
<td>5M, 4F</td>
<td>55.7 ± 8</td>
<td>15.9 ± 3.4</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1. Personal and Clinical Details of the 3 Subject Groups: Right Hemisphere Patients With Neglect (N+) and Without Neglect (N−), and Healthy Controls (HC)

Abbreviations: T, temporal; P, parietal; BG, basal ganglia; MCA, middle cerebral artery; F, frontal; Th, thalamus; Ic, internal capsule; Pu, putamen; Cl, claustrum; Cr, corona radiata; InC, insular cortex; I, ischemic; H, hemorrhagic; HA, hemianopia; LIQ, left inferior quadrantanopia.

aVisual field deficit as was found to confrontation.
bVisual neglect based on total score or scoring below individual test cut-off (in at least 2 subtests).
significantly higher compared with control subjects (except for patient N+ 3), with average times exceeding 2SD of the control mean.

The neglect group had significantly longer RT, $F(6, 833) = 60.8$, $P < .0001$, and lower detection rate, $F(6, 833) = 52.9$, $P < .0001$, for left than for right targets. Longer RT, $F(4,$
$F(4, 835) = 3.97, P = .0034$, were also found for near compared with far targets, where a significant difference was found between the far target and the nearest targets. Differences across the vertical dimension were not significant. Since the observed variations were different for each neglect patient, we further analyzed separately for each patient the effect of target locations. This allowed us to investigate whether patients exhibited simple or more complex perceptual deficits across space.

Within each patient, a one-way ANOVA was performed with target location as a factor. This was done separately for each spatial dimension, for both RT and correct detection as dependent variables. Table 2 shows the statistical results for each test. For the horizontal dimension, all neglect patients exhibited significantly longer RT for left than for right targets, indicating left neglect. Post hoc Bonferroni tests confirmed that RT for each target on the left side was significantly different from that of all other targets, indicating a gradual right-to-left increase in RT. Significantly smaller detection rates for left than for right targets were found for 7 of the 8 neglect patients, again indicating a right-to-left gradient change. For the radial dimension, significantly longer RT and lower detection rate were found for near than for far targets, only for patients N+ 1 and N+ 2. Post hoc tests revealed differences between the far target and the nearest targets. Differences in RT across the vertical dimension were significant only for 2 other patients (N+ 7 and N+ 8), indicating a spatial bias in favor of the lower and upper targets, respectively. Differences in detection rate were significant for patient N+ 8, but only approached significance level for patient N+ 7.

Experiment 2

Results from Experiment 1 indicated that 2 neglect patients (N+ 1 and N+ 2) performed poorly in both left and near space. We further questioned whether such deficits might be influenced by the rectangular arrangement of targets used. It might be that the observed bias could indeed be accounted for by a gradient of attention in the radial dimension. Alternatively, it could be accounted for by the targets’ location with respect to the angle in the field of view (polar reference; see Figure 3A). We therefore brought those patients back for a second testing (ie, Experiment 2) to examine whether deficits were best described using Cartesian or polar coordinates.

Subjects.

Five subjects who took part in experiment 1 participated in this experiment. These were 3 patients with neglect (N+ 1, N+ 2, and N+ 7) and 2 healthy controls (see
Table 2. F Statistic and Its P Value* for One-Way Analyses of Variance Performed for Each Spatial Dimension for the Neglect Patients

<table>
<thead>
<tr>
<th></th>
<th>Reaction Time</th>
<th>Correct Detection</th>
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<tbody>
<tr>
<td></td>
<td>Horizontal (F(6, 98))</td>
<td>Radial (F(4, 100))</td>
</tr>
<tr>
<td>N+ 1</td>
<td>41.1***</td>
<td>3.0*</td>
</tr>
<tr>
<td>N+ 2</td>
<td>37.4***</td>
<td>2.75*</td>
</tr>
<tr>
<td>N+ 3</td>
<td>25.6***</td>
<td>0.9 (ns)</td>
</tr>
<tr>
<td>N+ 4</td>
<td>12.9***</td>
<td>2.46 (ns)</td>
</tr>
<tr>
<td>N+ 5</td>
<td>13.3***</td>
<td>0.8 (ns)</td>
</tr>
<tr>
<td>N+ 6</td>
<td>53.6***</td>
<td>0.7 (ns)</td>
</tr>
<tr>
<td>N+ 7</td>
<td>6.7***</td>
<td>2.0 (ns)</td>
</tr>
<tr>
<td>N+ 8</td>
<td>11.9***</td>
<td>0.2 (ns)</td>
</tr>
</tbody>
</table>

*ns indicates not significant; *P < .05, **P < .01, ***P < .001.

Table 1 for details). Patient N+ 7 who only showed left (but not near–far) neglect in Experiment 1 served as control because of commonality of lesion site.

**Procedures.** Experiment 2 was designed in a similar way to that of experiment 1, except for the targets’ location. A total of 35 possible targets were distributed on a 7 × 5 (horizontal × radial) polar grid, a fan-like pattern of targets centered between the subject’s eyes (Figure 3B). The 7 targets on the first row (close to the subject’s body) were kept at the same location as in experiment 1. The horizontal angle (with respect to the subject’s head position) was then calculated for each of these 7 targets and was used to define the corresponding radial line. The remaining 28 targets were then placed on these 7 radial lines. As in experiment 1, only one target appeared within the scene at a time. The experiment included 304 trials (including catch trials).

**Statistical Analysis.** Linear regressions were performed with RT and percentage of correct detection as dependent variables. For each dependent variable, 4 regression models were tested where the independent variables were Cartesian coordinates (x, y; ie, horizontal and radial coordinates), polar coordinates (r, θ; ie, distance and horizontal angle), x-coordinate, or the horizontal angle θ.

**Results**

Reaction time and correct detection. Results indicated that the observed deficits were influenced by the spatial arrangement of targets used. Figures 3C and 3D show mean RTs and percentage of correct detection calculated for patient N+ 1. (Data for patient N+ 2, which are not presented here, showed similar results.) The striking findings clearly seen from the figure indicated that the wider the angle (increasing from midline toward the left), the poorer the visual information was processed. That is, performance was approximately the same for all targets that lay on a specific radial line, but overall got worse as angle increased. In contrast, patient N+ 7 who showed left neglect in experiment 1, similarly demonstrated deficits that depended mainly on the lateral direction. That is, RT increased and detection rate decreased for targets that appeared further to the left (Figures 3E and 3F).

To further examine which coordinate system better explains the observed behavior, linear regressions were performed with RT and detection rate as dependent variables. Table 3 shows the $R^2$ and $P$ value for each regression model performed for RT. Note that linear regressions for detection rate, which are not presented here, indicated similar results. Overall, results showed that both patients (N+ 1 and N+ 2) exhibited a much stronger dependence on the polar than the Cartesian coordinates. This held true even when only θ was taken into account, suggesting strong dependence on the angular coordinate. In contrast, patient N+ 7 exhibited a strong dependence on the x-coordinate for both grids. As one might expect, healthy control subjects exhibited no asymmetry across space for both grids.

The “theta-patient model.” We suspected that experimental target placement might bias results, so in an attempt to explain differences between experiments, we constructed an idealized model that simulated a “virtual patient” that has a pure dependence only on the angle from the sagittal plane (perceptual deficits purely depended on θ). The model was based on linear regression where we used data from patient N+ 1 to obtain the slope and intercept values for the model. Based on data from the neglect group, we further assumed an unvarying performance for detecting targets on the right side of space. We tested the model only for the middle layer of targets from experiment 1 (at eye level) and targets from experiment 2. The model calculated the predicted RTs for each target location (model output) while separately considering the θ, r, x-, and y-coordinates (model input). Figures 4A and 4B show the predicted RTs for targets in the Cartesian and polar grids, respectively.
The simulation clearly indicated an increase in RT as $\theta$ changed (from midline toward the left). However, remarkable results were seen for the depth dimension (ie, the distance from the body—$r$- and $y$-coordinates). When tested in a Cartesian grid, RT gradually increased as the targets appeared closer to the body. This held true for all columns of targets (Figure 4A, lower panel). This confounded result was in line with the observed behavior in experiment 1 that

Figure 3. An illustration of stimuli and results in experiment 2. (A) The relationship between the target location (black circle) and the angle in the field of view with respect to the subject’s midline (the angle from the sagittal plane). Note how the target located closer to the subject’s body lay on a wider angle. (B) An illustration of a subject sitting in front of the VRROOM (Virtual Reality and Robotics Optical Operations Machine) system, and the spatial arrangement of all possible virtual targets appearing within the 3-dimensional (3D) scene (using a polar grid of targets). (C) Mean reaction times and (D) percentage of correct detection are represented as 2D spheres (diameters are proportional to the calculated value as in Figure 1) for patient N+ 1. (E) Mean reaction times and (F) percentage of correct detection calculated for patient N+ 7.
Table 3. Linear Regression Models Performed on Reaction Times

<table>
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<tr>
<th></th>
<th>R²</th>
<th>P</th>
<th>R²</th>
<th>P</th>
<th>R²</th>
<th>P</th>
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<td>.655</td>
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<td>.926</td>
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<td>.925</td>
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<td>.638</td>
<td>&lt;.001</td>
<td>.904</td>
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<td>.896</td>
<td>&lt;.001</td>
<td>.353</td>
<td>&lt;.01</td>
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<td>&lt;.001</td>
<td>.671</td>
<td>&lt;.001</td>
<td>.276</td>
<td>&lt;.05</td>
<td>.848</td>
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<td>HC1</td>
<td>.147</td>
<td>ns</td>
<td>.203</td>
<td>ns</td>
<td>.024</td>
<td>ns</td>
<td>.094</td>
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<tr>
<td>HC2</td>
<td>.076</td>
<td>ns</td>
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<td>ns</td>
<td>.098</td>
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<td>.043</td>
<td>ns</td>
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</table>

Abbreviations: HC, healthy control; ns, not significant.

Figure 4. Predicted reaction times for each target location in the “theta-patient model,” presented according to θ, r, x, and y using (A) Cartesian grid (experiment 1) and (B) polar grid (experiment 2). Note that upper right panel (for x-coordinate) differs in scale from the corresponding panel in A.
predicted near neglect. Yet when tested in a polar grid, RT was not affected by the distance from the body. This held true along each radial line (Figure 4B, lower panel) and was in line with the observed behavior in experiment 2. Taken together, the model demonstrated how a deficit that depends only on polar angle could be misconstrued as near neglect if one uses rectangular array of targets such as in the standard paper-and-pencil tests.

General Discussion

The present study investigated whether neglect patients exhibit simple contralesional versus more complex perceptual deficits across a 3D space using the VESNA paradigm. Whereas our findings revealed both simple and complex asymmetries across several dimensions for subjects in the neglect group, the observed deficits were influenced by the spatial arrangement of targets. To our knowledge, the dependence on the horizontal angle exhibited by 2 neglect patients was the first behavioral evidence observed in neglect.

In clinical practice, the assessment of neglect is of fundamental importance to measure its severity, monitor changes, and plan effective treatment. Over the years both researchers and clinicians have used a variety of tests to detect and quantify neglect.20,21,48,49 The structure of the neglected space, however, is elusive and often difficult to characterize in a precise way using traditional tests. Studies that assessed neglect using these tests have reported neglect along different dimensions.11,12,14 These studies, however, only tested dimensions individually, or presented stimuli limited to a plane. For example, Jannink et al41 exposed subjects to a 3D scene that included depth cues but presented stimuli only on a 2D plane (ie, balls appearing from different view angles). The current study used VR to explore perceptual deficits associated with neglect by rigorously mapping a large volume of the workspace. Using a dense array of spatial locations (Cartesian and polar) that spans the full range of the 3D space, our paradigm allows determination of a specific subspace within a 3D space where a patient has the highest probability of missing a target. Indeed, all our neglect patients exhibited simple or more complex asymmetries across several dimensions for both detection rate and RTs, indicating a lateral bias of attention. Our paradigm is therefore able to detect inattention biases occurring in patients with stroke, and also be more sensitive to such biases than standard tests for neglect. Results from experiment 2 further strengthen the importance of using all 3 dimensions and considering the spatial arrangement of targets. When tested in a Cartesian grid, patients N+ 1 and N+ 2 appeared to perform poorly in left and near space. Yet when tested using a polar grid, these patients only showed a simple left side asymmetry that depended almost entirely on the horizontal angle but not distance.

Human and animal studies suggest that near and far space are coded within distinct representations in the brain; a notion supported by studies with neglect patients.12,13,50-52 Previous studies that investigated performance in near/far space have mainly used line bisection and cancellation tasks. Most of these studies have corrected for angular sizes of stimuli in near and far space. That is, they held constant the retinal angle across viewing distances, by increasing the stimulus size as viewing distance increased. However, line length has already been shown to affect bisection errors in both healthy individuals and patients.2 A recent study with healthy subjects that manipulated both linear and angular dimensions of stimuli has highlighted the importance of controlling for both stimulus factors.53 The authors have further suggested that controlling only for retinal angle might lead to false interpretation of the observed results (especially for far neglect).

Unlike those previous studies, the current study required subjects to detect a large set of targets that were placed in Cartesian and polar grids. Thus, the spatial arrangement of targets was manipulated rather than the stimulus factors. Interestingly, analogous to Wilkinson and Halligan,53 we demonstrated how a deficit that depends almost entirely on the horizontal angle (polar reference) could be misconstrued as near neglect if one uses rectangular array of targets. This was evident from both experiment 2 and the idealized model. Compared with previous studies that used paper-and-pencil tests or regular computer screens, we were able to detect such deficits not previously described, by probing the interactions between all dimensions. It should not be assumed, however, that we suggest that genuine near/far effects were not found in previous studies. It is well known that the nature of neglect behavior is not uniform across patients, where previous studies reported various types of neglect.24 This study therefore suggests that future studies should incorporate various 3D arrangements of targets to enable precise mapping of deficient areas.

Numerous studies suggested that neglect may be defined with respect to various reference frames, (eg, eye-, head-, and trunk-centered).22,54 One possibility is that our 2 patients who showed a dependence on the horizontal angle, exhibited different subtypes of neglect, which included eye-centered reference frame. Furthermore, patients with neglect exhibit impaired space exploration and are impaired at making saccades to contralesional targets.55,56 It is also possible that our patients tended to use more eye movements than most neglect patients, which may have affected our results, although we cannot draw conclusions about this since eye movements were not recorded. Because of this limitation (lack of eye orientation control for both experiments), it should be emphasized that both polar and Cartesian grids originated at a point relative to the subject’s head and are not necessarily retinotopic. A future study should combine...
experimental manipulations of head/eye orientation using eye movement recording.

Neglect has been suggested to emerge from a gradient of attention or spatial representation as a function of spatial location. In agreement with previous studies, the asymmetries exhibited by our patients were not a harsh transition but instead showed a gradual reduction of attention across space. Indeed, it is because our patients exhibited gradual changes that we were able to identify the effect of target arrangement on the observed deficits. A harsh transition on the other hand may have produced similar results irrespective of the arrangements of targets used.

One potential confound in our results is the fact that 2 patients in the neglect group had visual field defects in addition to neglect. However, the observed behavior of these patients did not significantly differ from that of the patients who had only neglect. Thus, the observed deficits were not exacerbated by the presence of visual field defects. The differences across the vertical dimension for patient N+ 8 were probably because of the presence of visual field defect.

Increasing task complexity can enhance test sensitivity. For example, the presence of distractors in the field of view increases the competition for attention. The current study used only single stimulus presentations in order to examine fundamental characteristics of perceptual neglect in 3D space. We showed that our simple paradigm was sensitive enough to characterize perceptual deficits across space, but a future study should examine neglect behavior in a more complex environment.

Finally, several studies have exploited the advantages of VR for providing controlled quantitative measures in detecting deficits associated with neglect. Our results are in line with these studies. Yet our VR approach further provides clinicians and researchers with a more precise description of a patient’s deficits, which could affect planning appropriate training protocols for this disabling heterogeneous disorder.

Acknowledgments
We thank S. Housman, K. Settle and A. Patel for their useful comments and skillful assistance. We gratefully acknowledge programming support by C. Scharver and VRCO for providing CAVELib and TrackD software.

Declaration of Conflicting Interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
This work was supported by the Michael Starnes Stroke Foundation (to A.Y.D); the National Institute of Health (R01 NS053606 to J.L.P); and the Department of Education, National Institute on Disability and Rehabilitation Research (H133FO80010 to A.Y.D). The opinions expressed here do not necessarily represent the policy of the Department of Education.

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