COLLISION JUDGMENTS OF PATIENTS WITH HOMONYMOUS FIELD DEFECTS

A thesis presented to the graduate faculty of New England College of Optometry in partial fulfillment of the requirements for the degree of Master of Science.

Kevin E. Houston, OD, FAAO

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Kevin Edward Houston, O.D.

This manuscript has been read and accepted by the Thesis Examination Committee in satisfaction of the thesis requirement for the degree of Master of Science.

6-19-14
Date

Alex R Bowers
Alex Bowers, M.C.Optom., Ph.D.
Graduate Faculty Advisor

Eli Peli
Eli Peli, M.Sc., O.D.
Graduate Faculty Advisor

Shirin E. Hassan, B.App.Sc.(Optom), Ph.D.
Thesis Committee Member

Richard Jamara
Richard Jamara, O.D.
Thesis Committee Member

7-16-14
Date

Nancy J Coletta
Nancy J. Coletta, O.D., Ph.D.
Director of Graduate Studies

New England College of Optometry

Abstract

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Kevin E. Houston

New England College of Optometry, 2014

Background: After stroke, colliding with obstacles or drifting left or right while walking or wheelchair driving are common problems which have been attributed to motor impairments and homonymous visual field defects (HFDs) impairing blind side detection. However, misjudgment of obstacle location related to dysfunctional visuospatial processing from damage to higher visual-cortical areas may also contribute. While the impact of the HFD on detection is reasonably well documented in walking and simulated driving tasks, relatively little is known about the ability of patients with HFDs to judge collisions once an obstacle is detected. My thesis aims to address this gap in knowledge by measuring collision judgment behaviors of patients with HFDs. **Methods:** Patients with HFDs, n=29 and normal vision (NV), n=21 were seated in front of a large screen which visually simulated walking. They responded "yes I will collide" or "no I will not collide" for a human figure appearing at various lateral offsets from the virtual walking path and threshold was calculated and compared within-subjects for blind and seeing sides. The difference between blind and seeing side thresholds (asymmetry) was compared between groups by side of field loss. Asymmetry was compared alsoto lane position in a driving simulator, mobility on an indoor obstacle course, self-reported mobility difficulties, and line bisection test performance. **Results:** NVs, patients with right HFDs (n = 11), and left HFDs without neglect or neglect history (n = 8) exhibited symmetrical collision thresholds (same on blind and seeing sides).

However, the remaining patients with left HFD, both those testing positive for neglect and those with a self-reported history of neglect (n = 10), showed significant negative asymmetry in collision judgments (p=0.008) smaller on the left and larger on the right. It was as though their body midline were rotated or shifted rightward. Left HFD patients with a history of neglect showed this asymmetric behavior despite passing typical paper and pencil neglect tests. Stepwise multiple linear regression analysis confirmed that neglect /neglect history was the only significant predictor of collision judgment asymmetry. In the driving simulator, the neglect /neglect history group had an average lane position that was significantly offset to the right (p=0.006), the magnitude of which showed no correlation to the magnitude of collision judgment asymmetry. Asymmetry in collision judgment was correlated with lower percent preferred walking speed in the obstacle course (p=0.04) and greater variability on line bisection (p=0.03). **Conclusions:** A current diagnosis or a history of left neglect in HFD patients results in asymmetric collision judgments, allowing obstacles closer to the path of movement on the left side and further out on the right side before judging them as a collision risk. This spatial misjudgment may cause collisions even when an obstacle is detected. These behaviors likely represent the spatial misperceptions in body midline described previously in patients with left neglect. This data is preliminary evidence that the asymmetry affected actual mobility, manifesting as a significant rightward lane offset in a driving simulator and a slowed walking speed in an obstacle course. Common paper and pencil neglect tests did not predict collision judgment asymmetries.

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1.0 General Introduction

After stroke, colliding with obstacles or drifting left or right while walking or wheelchair driving are common problems (Turton, Dewar, Lievesly, O'Leary, Gabb & Gilchrist, 2009) which have been attributed to motor impairments (Boyadjian, Marin & Danion, 1999) and homonymous visual field defects (HFDs) impairing blind side detection (Bowers, Mandel, Goldstein & Peli, 2009, Papageorgiou, Hardiess, Ackermann, Wiethoelter, Dietz, Mallot & Schiefer, 2012a). However, misjudgment of obstacle location related to dysfunctional visuospatial processing from damage to higher visual-cortical areas may also contribute to these mobility problems. While the impact of the HFD on obstacle detection is reasonably well documented in walking and simulated driving tasks (Bowers et al., 2009, Papageorgiou et al., 2012a), relatively little is known about the ability of patients with HFDs to judge collisions once an obstacle is detected. My thesis aims to address this gap in knowledge by measuring collision judgment behaviors of patients with HFDs.

1.1 Homonymous Field Defects

HFDs are defined as loss of part or all of the visual field on the same side in both eyes resulting from damage to the post-chiasmal visual pathway including the post-chiasmal optic tract, lateral geniculate nucleus of the thalamus, optic radiations, and occipital cortex (V1) (figure 1). The vascular supply for the post-chiasmal visual pathway is from the middle cerebral artery via the internal carotid, and the posterior cerebral artery via the vertebral artery. HFDs can be congruous or incongruous, complete or incomplete, and relative or absolute. If the amount of field loss is similar in both eyes, this is termed congruous. It is a

general rule that more posterior strokes produce HFDs with greater congruency. Giorgi et. al. (2009) defined complete HFD as ≤5° of residual vision on the hemianopic side of the vertical meridian within 20° above and below fixation assessed with a Goldmann V4e. The visual loss itself also has levels of severity from a relative depression in visual sensitivity of all or part of the hemianopic field, to no light perception (absolute).

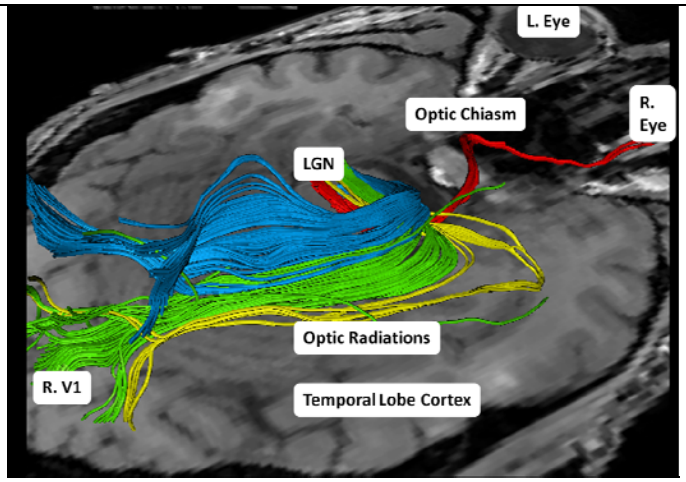


Figure 1: Diffusion tensor imaging (DTI) labeling the white matter tracts of the right primary visual pathway, which transmit the left visual hemifield to the occipital cortex V1. Note that the nasal tract between the left eye into the chiasm is not labeled in this DTI, but also represents this pathway for the left hemifield. Damage posterior to the optic chiasm results in left homonymous field defects. Damage to the right superior optic radiations (blue fibers) results an inferior left quadranopia and is associated with damage in the overlying parietal cortex, whereas damage to the right inferior optic radiation (green fibers) results in a superior left quadranopia and is associated with damage to the overlying temporal cortex.

1.2 Homonymous Field Defects and Visuospatial Dysfunction

In patients with HFDs, in addition to damage to the optic radiations or V1, there is also often damage to posterior parietal and temporal cortex which overlies the optic radiations (figures 1 and 2). Since they are anatomically juxtaposed and both fed by the middle cerebral artery distribution (Kline, Bhatti, Chung, Eggenberger, Foroozan, Glolnik, Kawasaki & Shaw, 2011), when blood supply is interrupted or sometimes when there is hemorrhage or mass, often both structures are affected. These cortical visual areas contain multiple copies of highly organized neural representations of visual space (referred to as visuotopic maps) (Swisher, Halko, Merabet, McMains & Somers, 2007) and mediate visuomotor transformations (Jackson & Husain, 2006, Thier & Karnath, 1997), visual attention (Adair & Barrett, 2008

), and spatial localization (Bisiach, Luzzatti & Perani, 1979, Medina, Kannan, Pawlak, Kleinman, Newhart, Davis, Heidler-Gary, Herskovits & Hillis, 2008). Damage to the parietal lobes has been shown to negatively affect performance on collision judgment tasks (Assmus, Marshall, Ritzl, Noth, Zilles & Fink, 2003, Papageorgiou, Hardiess, Wiethoelter, Ackermann, Dietz, Mallot & Schiefer, 2012b) and is correlated with the behavioral syndrome of hemispatial neglect (Corbetta, Kincade, Lewis, Snyder & Sapir, 2005).

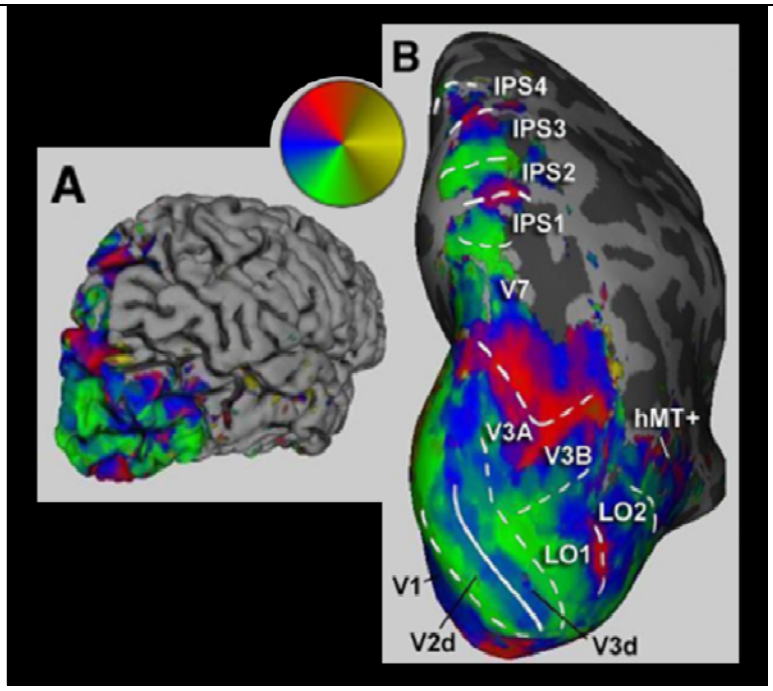


Figure 2: A) View as though looking at the brain from the back (occipital pole), showing visuotopic maps (colored areas) for the left hemifield (color coded circle) as measured with functional MRI visuotopy. B) Enlarged (and flattened) view of (A) showing the boundary lines and labels for the various known regions in the human visual areas containing visuotopic maps. Each region contains a copy of the map for the left hemifield (this is the right hemisphere; left hemisphere contains similar maps for the right hemifield). Damage to the cortical maps representing visual space, particularly in the right parietal cortices, is thought to cause problems localizing sensory stimuli, particularly in relation to the body. Stroke and brain injury patients with damage to the right inferior parietal lobe often exhibit left hemispatial neglect, characterized by rightward deviated judgments of straight-ahead.

IPS= Intra-Parietal Sulcus, MT=Middle Temporal, LO=Lateral Occipital

1.3 Collision Envelope

There is precedent for studying collision judgments in the normally-sighted (Woods, Shieh, Bobrow, Vora, Barabas, Goldstein & Peli, 2003) and tunnel vision patients (Apfelbaum, Pelah & Peli, 2007) by measuring the collision envelope for life-sized human obstacles in a walking simulator (figure 3). The collision envelope theory of collision judgment suggests that each person maintains an internal representation of the volume of space they occupy (referred to as the collision envelope) to calculate when an external object poses a collision hazard (Woods et al., 2003). The outer edge of this space is the individual's collision threshold (which is intended to represent the perceived safe passing distance). The collision envelope was approximately symmetrical in the normally sighted and tunnel vision patients, and interestingly was not correlated with physical size (although wearing a "sandwich board" to increase body width did increase the envelope) (Apfelbaum et al., 2007, Woods, Lichtenstein, Mandel & Peli, 2006, Woods et al., 2003). However, the tunnel vision patients were found to have larger (but still symmetrical) collision thresholds than the normally sighted, possibly as a compensatory strategy for their visual field loss (Apfelbaum et al., 2007).

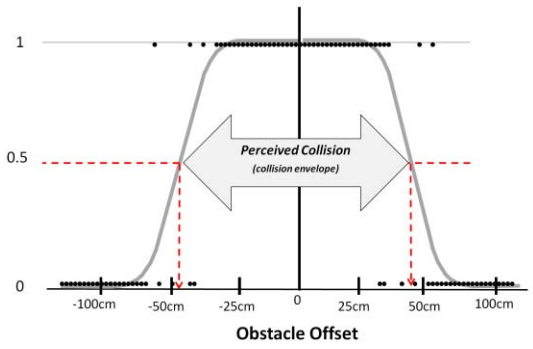


Figure 3: Illustration of the raw data of a normally sighted subject fitted with a cumulative Gaussian on the right and left to determine the collision threshold for right and left sides respectively, at 50% (red dashed arrows pointing to the x-axes). "Collision" responses are assigned a 1 and "no collision" a 0. Obstacle offset refers to the distance of the obstacle from the virtual walking path.

1.4 Collision Envelope and Homonymous Field Defects

The collision envelope of patients with HFDs has not been investigated previously; however, it has been indirectly evaluated in driving studies. Bowers et al found that, while drivers with normal vision maintained a central lane position in a driving simulator, people with complete hemianopia adopted an average lane position away from the side of field loss, possibly representing an enlarged blindside collision threshold, which may be compensatory (Bowers, Mandel, Goldstein & Peli, 2010). A similar behavior was documented by Wood et al in an on-road study of drivers with HFDs (Wood, McGwin, Elgin, Vaphiades, Braswell, DeCarlo, Kline & Owsley, 2011). It is reasonable to hypothesize that when making collision judgments patients exhibit a larger collision threshold on their blind side as a compensatory strategy.

1.5 Left Hemispatial Neglect

When studying stroke and brain-injured patients with left HFDs, left hemispatial neglect must be considered as they often occur together. Left neglect is a behavioral syndrome which occurs after approximately half (48%) of all right hemisphere strokes (Buxbaum, Ferraro, Veramonti, Farne, Whyte, Ladavas, Frassinetti & Coslett, 2004). It is characterized by a resting rightward gaze preference (Berger, Johannsen & Karnath, 2008), reduced scanning to the left hemifield,(Behrmann, Watt, Black & Barton, 1997) decreased response to all types of sensory stimuli on the left (Heilman, Bowers & Watson, 1983), and deviated judgments of straight ahead to the right (Brain, 1941, Heilman et al., 1983, Schenkenberg, Bradforn & Ajax, 1980). It has been widely suggested that the root cause of left neglect is a shift in the internal representation of body position to the right (Brain, 1941, Chokron, 2003, Karnath, 1994b, Vallar, 1998, Ventre, Flandrin & Jeannerod, 1984). This "egocentric shift hypothesis"(Chokron, 2003, Karnath, 1994b) is supported by studies showing that left neglect most often respects the midline of the patient's trunk (Karnath, Fetter & Niemeier, 1998, Karnath, Schenkel & Fischer, 1991).

1.6 Neural Correlates of Left Neglect

The brain regions most highly correlated with left neglect are the right posterior temporal and inferior parietal lobes, often referred to as the temporal-parietal junction, TPJ (right ventral frontal lobe is also correlated) (Corbetta et al., 2005). In a lesion analysis study, viewer-centered left neglect (which respects the midline of the trunk) correlated with damage in the

parietal lobes, whereas object-centered neglect (which respects gaze position, i.e. retinotopic) correlated with damage in the temporal lobes (Medina et al., 2008).

1.7 Neural Correlates of Egocentric Perception

Visuotopic maps in primary visual cortex code location based on where the retina was stimulated, regardless of the eye's position in the orbit (figure 4). So how does our brain know if an object is to our left or right and thereby formulate a movement towards it? Egocentric perception (internal representation of the location of body parts to one another) has been conceived of to solve this problem and theoretically relies on a coordinate system similar to the visuotopic maps. In the eye movement literature, these egocentric maps are referred to as spatiotopic maps (Duhamel, Bremmer, BenHamed & Graf, 1997) and in the motor research literature, the internal reference frame (Redding & Wallace, 1997). Behavioral studies from prism adaptation literature studies led to subdivision of the internal reference frame into head-centered and body-centered , among others (Redding & Wallace, 1997). Visuotopic maps could fit this nomenclature by referring to them as the eye-centered reference frame, whereas the head-centered reference frame refers to the sum of the eye-in-head coordinate and visuotopic coordinate (analogous to gaze tracking paradigms).

Evidence for a neural correlate of a spatiotopic "head-centered" map exists from single cell recording in primates and fMRI in humans. Activity was measured in the temporal or parietal lobes (depending on the type of stimulus) in response to changes in eye position when the retinal stimulation did not change (Bremmer, Kubischik, Pekel, Hoffmann & Lappe, 2009, d'Avossa, Tosetti, Crespi, Biagi, Burr & Morrone, 2007, Duhamel et al.,

1997). A neural correlate for the body-centered reference frame has yet to be identified, however fMRI studies have identified brain networks which are likely involved. When performing an egocentric task requiring a judgment of the alignment between a vertical line and body midline, fMRI measured bilateral but primarily right-hemisphere activity in the posterior intraparietal sulcus, superior parietal lobule, superior occipital gyrus, and the angular gyrus of the inferior parietal lobule (Vallar, Lobel, Galati, Berthoz, Pizzamiglio & Le Bihan, 1999). Bottini et al argued that egocentric perception arises from multiple sensory inputs including vestibular, proprioception, and vision; and so only a few brain regions (insula, temporoparietal junction, and somatosensory area II) have the inputs to handle this task (Bottini, Karnath, Vallar, Sterzi, Frith, Frackowiak & Paulesu, 2001).

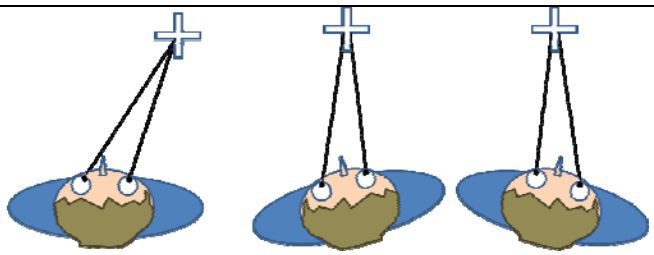


Figure 4: The person illustrated is foveating the plus with their head and body in three different positions and rotations. Visuotopic maps measured by fMRI would be the same for the 3 different situations illustrated, however in order to move towards the plus the person's brain must know where the plus is in relation to the torso. The concept of an egocentric coordinate system provides a solution to this problem. It maintains the location of visuotopic objects (ie. the plus) in relation to the motor systems involved in the planned movement (in this case, the torso).

1.8 Tying it All Together: Neglect, Egocentric Perception, and Collision Judgments

The temporoparietal junction is the most frequently injured brain region in left hemispatial neglect (Corbetta et al., 2005) and, as discussed in the prior paragraph, a prime location for neural maps for egocentric perception. If the egocentric shift hypothesis of neglect is correct, left HFD patients with left neglect from damage to the right posterior parietal and/or temporal lobes should perceive the center of their body as being rotated right or translated further to the right than it actually is. I elaborate on this distinction in the discussion. If neglect patients have rightward errors in egocentric localization, collision judgment behaviors should be opposite that of patients with HFDs without left neglect. Specifically, patients with left neglect should allow obstacles to come closer to the path of movement on the left and further away on the right before reporting "collision" (Figure 5).

1.9 Aims and Hypotheses

In summary, the overall aim of this study was to characterize the collision judgments of patients with HFDs, either without or with left neglect, using the collision envelope paradigm previously implemented for normally-sighted observers and patients with tunnel vision.

Our primary hypothesis was that patients with HFDs without left neglect would exhibit larger collision thresholds on their blind side, but that patients with left neglect would reporting obstacles as not posing a collision hazard when they are closer to the path of movement on the left side and further out on the right side (figure 5).

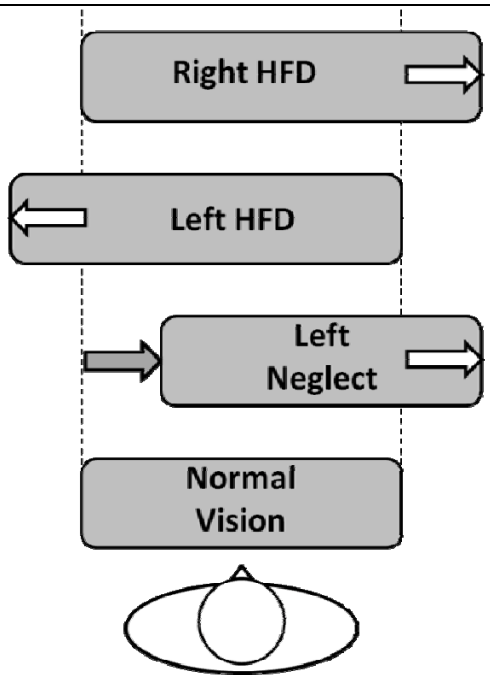


Figure 5: Grey-shaded rectangles represent the hypothesized collision envelopes showing an increase on the blind side in HFD patients without (measured) neglect and a uniform rightward shift in those with left neglect.

In secondary analyses, we evaluated the relationship between performance on the collision judgment task and self-reported mobility difficulties, testing the hypothesis that those with more impaired collision judgments would report greater mobility difficulties. In addition, as some of the HFD participants had also participated in an ongoing driving simulator study(Bowers, Houston, Goldstein & Peli, 2014a) and an ongoing obstacle course study (Pundlik, Tomasi & Luo, 2014), we evaluated the relationship between collision

judgment threshold asymmetry (difference between blind and seeing side threshold) and performance on these more interactive mobility tasks.

2.0 Methods

2.1 Participants

Patients with HFDs resulting from cerebrovascular accident (CVA - ie. stroke, aneurysm, etc) were recruited from local Boston-area hospitals and eye care practices. Inclusion criteria were: presence of HFD (complete or incomplete hemianopia) on Goldmann perimetry with V4e stimulus; ≥3 months since the CVA; binocular visual acuity of at least 20/40; and a normal visual field on the seeing side. Schenkenberg Line Bisection (Schenkenberg et al., 1980) and Bells Test (Vanier, Gauthier, Lambert, Pepin, Robillard, Dubouloz, Gagnon & Joannette, 1990) were used to classify participants as having left hemispatial neglect. Mental status was documented using the Mini-Mental State Exam (Folstein, Folstein & McHugh, 1975).

Fifty-two patients were screened of which 31 met the study criteria and were enrolled. Two patients who tested positive for right neglect were enrolled but later excluded as this condition is uncommon and inherently different (neurologically and behaviorally) from left neglect (Beis, Keller, Morin, Bartolomeo, Bernati, Chokron, Leclercq, Louis-Dreyfus, Marchal, Martin, Perennou, Pradat-Diehl, Prairial, Rode, Rousseaux, Samuel, Sieroff, Wiart & Azouvi, 2004). Thus 29 were enrolled and completed the study and were included in data analyses; 11 right HFDs and 18 left HFDs, 5 of whom scored positive for left neglect on line bisection and bells cancellation (table 1).

Additional background data were collected from participants, including radiology reports (when available), a detailed medical and ophthalmic history which included (among other things) the time since vision loss, physical medicine and neuropsychological history (including 3 questions about a prior history of left neglect), and vision rehabilitation treatment history.

Table 1. Characteristics of the HFD Participants

	Right HFD*	**Left HFD^**	Test for between group difference
Total	11	18	
Female, n (%)	5 (45%)	5 (28%)	Fishers exact p=0.461
Age, yrs mean (SD)	56 (±19)	58 (±18)	t=-0.284, df=27, p=0.782
Yrs since onset, mean (SD)	6.7 (±5)	6.7 (±6)	t=0.015, df=27, p=0.988
MMSE[§] (x/30), mean (SD)	26 (±3)	27 (±5)	t=-0.198, df=19, p=0.845

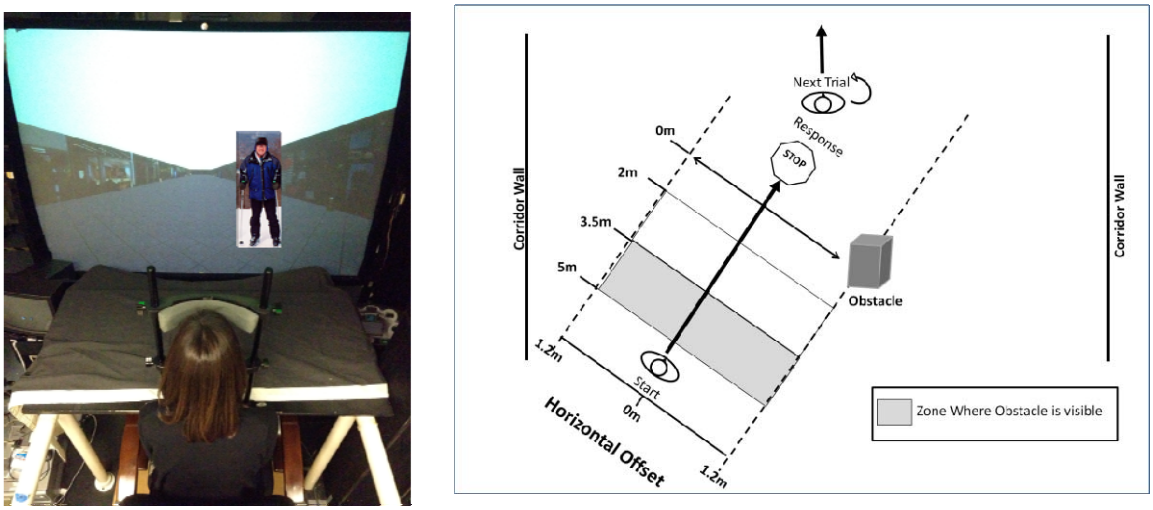
*Right HFD=Right Homonymous Field Defect, ^Left HFD=Left Homonymous Field Defect, [§]Mini-Mental State Exam

In addition, 21 naïve volunteers (31 ± 9 years, 48% female) with normal vision (NV) were recruited from Schepens as a control group and to provide data on the collision judgment symmetry of normally-sighted observers for the experimental set up used in this study, i.e. seated with head restrained. Symmetry of the collision envelope has previously been reported for NV participants; however, in that study they completed the collision judgment task while standing and without any head restraint.(Woods et al., 2003)

2.2 Collision judgment measurements

2.2.1 Set up

To eliminate motor impairment as a confounding variable, participants performed the collision judgment task when seated, enabling a purely visual judgment to be measured. Their head was stabilized in a headrest-chinrest mounted on a black table top (which restricted visual reference of body position) 100 cm from a wide (94° × 79°) rear-projection screen displaying a video model of an actual shopping-mall corridor (fig 6a). The headrest was necessary to keep the head aligned with the center of the virtual corridor and limit postural shifts. Care was taken to remove any items from view which were between the screen and the patient to prevent them from being used as an unnatural landmark to aid collision judgments. The animated mall corridor generated an optic flow background at 1.5m/sec along a straight path similar to that experienced during actual locomotion.



(a) (b)

Figure 6. Virtual reality mall walking simulator set-up and collision judgment task. a) Photograph of participant performing the experimental task showing the mall with life-sized human obstacle. b) Schematic of a virtual walking trial. The corridor moved as though the patient were walking at 1.5m/s along various predetermined trajectories (heavy black arrow). The obstacle appeared when the subject was 5m away, was visible while the subject was in the gray zone, and disappeared after 1s (when the subject was 3.5m from the obstacle). The horizontal offset of the obstacle from the walking path varied on each trial.

2.2.2 Collision Judgment Task

Each participant performed the collision judgment task with gaze unconstrained (freely scanning), wearing spectacle correction when appropriate. Each trial consisted of "walking" one straight segment of the path when suddenly a single life-sized human figure appeared either directly in the virtual path of movement, or at different offsets to the left or right of the path. The figure appeared at a virtual distance of 5m from the participant and was visible for 1 second. The figure then disappeared (at a virtual distance of 3.5m) and the optic flow ceased, signaling the end of the trial. Participants were instructed to "*imagine walking down an actual mall corridor"* and to report verbally whether they would make any contact with the human figure if they continued on the same path, assuming they could not adjust their body or change direction to avoid the collision. A forced choice paradigm required a verbal response of "*collision or no collision*", or "*nothing*" if no person was seen. The scene then rotated to the next trajectory and the next trial began.

A session consisted of 80 trials (40 per side) and 8 catch trials where no obstacle was presented (9% (8/88)). There were 40 evenly spaced horizontal offsets (measured from the inside edge of the obstacle) providing a maximum angle of eccentricity of 19° (virtual offset 1.2m at a 3.5m z-axis distance), presented in a randomly determined order. The trajectory of walking was randomly changed for each trial so that it simulated either walking directly down the center of the mall corridor or diagnonally at 30-45° to the left or right (fig 6b). A practice session composed of twenty trials was conducted prior to each session starting out very easy (coming directly at them or far off to the side), and becoming progressively more difficult. Each session lasted about 45 minutes. The study design was to perform just one

session of the collision judgment task (88 trials); however 79% performed the task multiple times (up to 4) as part of another study with identical methodology (mean of 2.6 assessments (228.8 total trials) per individual), and this data was included in the analysis.

2.2.3 Collision Judgment Threshold

Collision judgment data were collected from the walking simulator program (C++), and imported into Matlab (Mathworks, Natick MA). The 80 non-practice response values were scored as 1 for collision and 0 for no collision. Detection failures were assigned a "no collision" value for analysis, with the rationale that having failed to detect the obstacle it would not have been considered a collision threat by the participant. Data for each participant were then fit with a cumulative Gaussian to derive the collision threshold (at 50%) for the left and right sides (then converted to blind and seeing sides), see figure 3. The fits were performed for each session and for data pooled across all sessions.

Two main measures were used in analyses: **collision judgment asymmetry** (blind side collision threshold minus seeing side collision threshold) and the overall **collision envelope width** (the sum of the absolute value of the thresholds for the two sides). Asymmetry is negative when the collision behavior is maladaptive (threshold smaller on the blind side than the seeing side). In preliminary analysis of the raw data, two patients exhibited large collision envelopes, responding "collision" on most trials, which could not be fitted with a cumulative Gaussian. One left HFD patient with neglect responded "collision" on every trial except one, and another patient (left HFD with neglect history but negative on the bells and line bisection tests) responded "collision" for all trials on the right (seeing) side.

Both showed this behavior on two or more sessions, despite repeating the instructions and asking the patient to report where on their body they would have bumped the obstacle. As far as could be determined, their responses were valid (they perceived that they would have collided). A threshold could not be calculated in these cases and so they were instead assigned an arbitrary value of 200cm (maximum testable eccentricity was 120cm). Whether this arbitrary value in anyway influenced the results was evaluated by repeating the main analyses with alternative arbitrary values of 150cm and 250cm and when excluding them; the interpretation of the results was exactly the same.

2.3 Other Mobility Measurements

2.3.1 Mobility Questionnaire

HFD patients were administered a short, 11-item questionnaire that addressed perceived difficulties with mobility in a range of situations (including walking in familiar and unfamiliar areas, crowded areas, outdoors, noticing objects to the side and avoiding obstacles when walking (see a copy of the questionnaire in the Appendix A). Difficulty was rated on a 5-point scale from 1 (no difficulty) to 5 (extreme difficulty) or 0 (not applicable). The questionnaire was previously developed for studies evaluating patients with hemianopia wearing peripheral prism glasses (Bowers, Keeney & Peli, 2014b, Giorgi, Woods & Peli, 2009) and included some questions from the Independent Mobility Questionnaire (Turano, Geruschat, Stahl & Massof, 1999). Overall perceived difficulty was computed as the median of the ratings for 8 of the 11 items. Three items were excluded as they were either not

relevant to collision judgments (questions 8 and 9, going up or down steps) or the situation was applicable to only a few participants (question 2, school / work).

2.3.2 Driving Simulator Task

Seventeen HFD patients completed a driving simulator assessment as part of another ongoing study(Bowers et al., 2014a). The methods and analysis have been reported in detail previously (Bowers et al., 2010) and are summarized here. Patients drove five 10-minute drives in a driving simulator; 3 on city roads and 2 on the highway. The position of the virtual vehicle was recorded by the driving simulator and subsequently analyzed to determine the lateral lane offset of the middle of the front axle of the car from the center of the travel lane. The median lateral lane offset for straight road segments (n = 12 per subject) was used in analyses.

2.3.3 Obstacle Course

Eight of the HFD patients who performed the collision judgment task also performed an obstacle course assessment as part of another ongoing study ((Pundlik et al., 2014). The indoor course comprised low level, hanging, and human-sized obstacles (46 obstacles total) (figure 7). Baseline walking speed was measured in a straight 27m long hallway without any obstacles. Patients then completed a practice walk through a short course to become familiar with the task and the nature of the different obstacles and then completed 4 loops of the test course. The experimenter recorded the number of collisions (any contact with an obstacle) and the time required to complete each loop. The session was video recorded to provide

documentation and reference if needed. Two main measures of mobility performance were used in analyses: the number of collisions and the percent preferred walking speed (obstacle course walking speed divided by hallway obstacle-free walking speed times 100) (Patel, Turano, Broman, Bandeen-Roche, Munoz & West, 2006).



Figure 7: Photo of the obstacle course that included inflatable palm tree obstacles, an actual human obstacle (experimenter in yellow shirt) and hanging obstacles (flags and shopping bags) (total 46 obstacles). The tables in the middle acted as a divider, with one loop being one trip around. The second experimenter (maroon shirt) recorded the number of collisions and time to complete the course.

2.4 Statistical Analysis

NV participants were assigned a "blind" side in a counterbalanced manner. HFD patients were grouped by side of field loss and presence of left neglect. Collision thresholds for each of these four vision groups (NV, right HFD, left HFD, left neglect) were first analyzed using a within-subjects comparison (Wilcoxon signed ranks test) of the thresholds on the blind compared to the seeing sides. The *Collision Judgment Asymmetry* (blind minus seeing side

threshold) and *Width* (blind plus seeing side threshold abs values) were then analyzed with a non-parametric one-way analysis of variance (Kruskal-Wallis test) with vision group as the between subjects variable, followed by pairwise between-group comparisons (Mann-Whitney U tests) with Bonferroni correction when appropriate.

During the preliminary analyses, it was determined that left HFD patients with a history of neglect behaved more similarly to those who scored positive for neglect than to those without neglect. The above analyses were therefore repeated with patients regrouped as: NV, right HFD, left HFD (no neglect history) and neglect-history (left HFD with a history of neglect or who tested positive for neglect). All subsequent analyses then used this new grouping as it best reflected the group behaviors.

Other factors that might affect the asymmetry including age, duration of vision loss, and detection failures were evaluated with forward stepwise multiple linear regression (Tabachnick & Fidell, 2001).

Secondary analyses of the relationships between collision judgment asymmetry and self-reported mobility difficulties, lateral lane offset (from the driving simulator), and performance on the obstacle course were evaluated using Spearman's rho.

All statistical analyses were performed with SPSS 11.5 2002 (IBM, NY); an alpha value < 0.05 was taken to indicate statistical significance and Bonferroni correction was applied for multiple comparisons.

3.0 Results

3.1 Detection Failures for Blind and Seeing Sides

Most HFD patients had only low rates of failing to see the life-sized obstacle (Table 2). Although there was a trend for left neglect participants to have higher detection failure rates, between group differences were not significant (Kruskal-Wallis p=0.162). There were no detection failures on the seeing side and NV participants did not have any detection failures.

Table 2: Median (interquartile range) for collision judgment measures with the original grouping of participants by side of field loss and positive testing for left neglect.

Group	n	Blindside Threshold (cm)	Seeing Side Threshold (cm)	Asymmetry (Blind – Seeing) (cm)	Collision Envelope Width (Blind + Seeing) (cm)	Blind side % detection Failures
NV	21	46 (39 to 58)	46 (39 to 53)	0.3 (-4 to 5.4)	86 (78 to 114)	0
Right HFDs	11	42 (30 to 68)	46 (30 to 59)	-0.6 (16 to 11)	76 (66 to 137)	5 (0 to 13)
Left HFDs	13	37 (22 to 44)	50 (35 to 60)	-11 (-27 to -5)	77 (72 to 100)	3 (0.2 to 5)
Left Neglect (+bells/LBT)	5	28 (23 to 120)	79 (46 to 155)	-24 (-61 to -11)	119 (70 to 268)	23 (5 to 42)

LBT = Line Bisection Test

3.2 NV Subjects Showed Symmetric Collision Judgment Behavior

The collision thresholds of the NV group were symmetric, consistent with prior reports (Woods et al., 2003) (median "blind" CE 46cm, "seeing" CE 46cm, p=0.305 Wilcoxon Signed Ranks).

3.3 Collision Judgment Asymmetries of HFD Participants

Collision judgment asymmetry refers to the difference between the blind side collision threshold and the seeing side collision threshold.

3.3.1 Collision Asymmetry at Each Session

Seventy-nine percent (23/29) of HFD patients completed at least two sessions of the collision judgment task, and 17 completed three sessions, with a mean of 2.6 sessions (228.8 mean total trials) per individual. Overall, there were no significant differences in collision judgment asymmetry between sessions (visits) 1, 2, and 3 (median session 1 was -11cm (-29 to 1), session 2 was -9cm (-30 to -2), and session 3 was -7cm (-26 to 7); Friedman, n=17, p=0.589). However, there were clearly some patients with large between-session differences (Figure 8). We expressed the overall group test-retest repeatability using the coefficient of repeatability, ie. 1.96 times the standard deviation of the differences in the means (Bland & Altman, 1986). This coefficient of repeatability (CoR) was 33cm for visits 1 & 2 (n = 23) (figure 8) and 37cm (n = 17) for visits 2 and 3 (not shown). A non-parametric version using 1/2 the range of the 5^{th} and 95^{th} quartiles found very similar results (30.5cm and 38cm respectively).

As there were no overall between session differences, the subsequent analyses of collision judgment asymmetries use thresholds computed for data combined across all sessions.

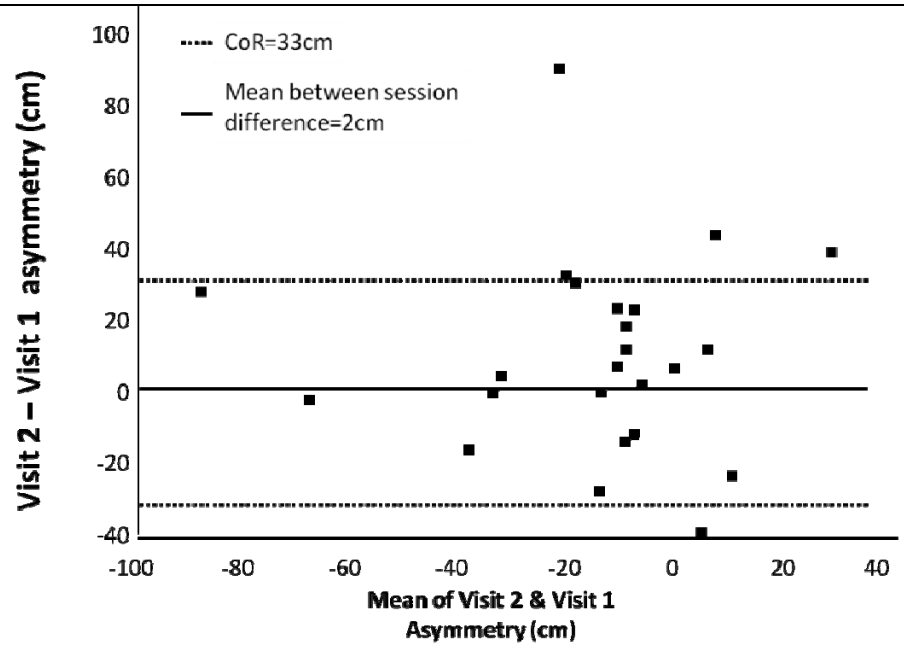


Figure 8: Bland-Altman plot showing the difference in collision asymmetry between sessions 1 and 2 plotted against the mean difference for the two sessions. The mean difference was 2cm (solid black line). The dashed lines represent the standard deviation of the mean between session differences times 1.96 (a measure of the coefficient of repeatability, CoR).

3.3.2 Collision Asymmetries for Each Group

It was predicted that both right and left HFD patients (without neglect) would show larger collision thresholds on their blind side (a positive asymmetry value), figure 9a. However, contrary to our predictions no positive asymmetry values were measured in any of the HFD groups (table 2, third column). The threshold was significantly smaller on the blind than the seeing side (negative asymmetry) in the left HFD group (n=13, Wilcoxon, p=0.005) and borderline in the left neglect group (n=5, Wilcoxon, p=0.07), but was not significantly different on the blind and seeing sides in the right HFD group (n=11, Wilcoxon, p=0.929), figure 9b.

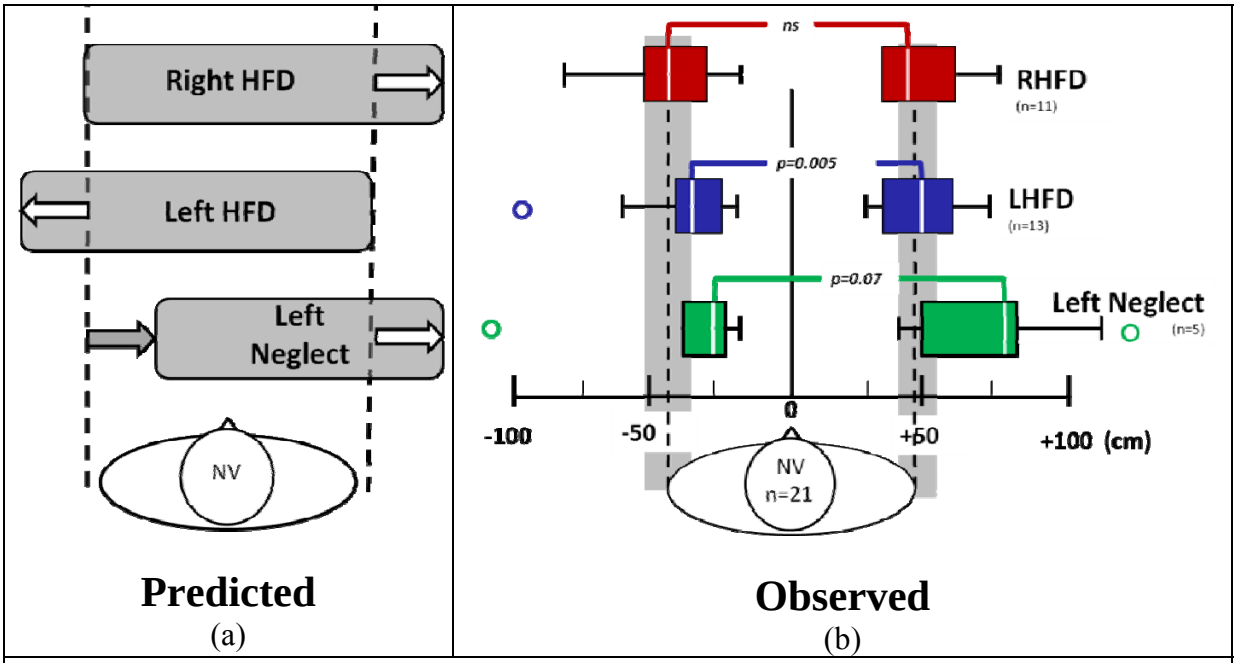


Figure 9: a) Predicted behavior during collision judgments with increased blind side thresholds for right and left HFD (arrows) and a rightward deviation for left neglect. The dashed lines represent the predicted NV collision envelope. Grey-shaded rectangles represent the predicted collision envelope with an increase on the blind side and a uniform rightward shift in those with neglect.

b) Observed collision envelope of the 3 original experimental groups compared to the NV group data (dashed lines (median) within the grey shaded area (IQR)). Ends of the colored boxes represent the interquartile ranges, the white lines are the median thresholds, error bars are the ranges, and outliers are circles of corresponding colors. Left HFD patients showed a significant negative asymmetry, allowing the obstacle in the walking simulator closer to the path of virtual movement on the blind side compared to the seeing side before judging it as a collision risk. Left neglect patients exhibited a more pronounced version of this behavior with smaller left side and larger right side threshold as though their body was perceived as being further to the right than it actually was.

There were significant between group differences in collision judgment asymmetries (Kruskal-Wallis, p=0.001). Posthoc analysis confirmed that the left HFD and left neglect groups had significantly greater negative asymmetry than the NV group and a trend for greater asymmetry than the right HFD group (table 3 and figure 10b).

Table 3: P-values for post hoc pairwise between-group comparisons of collision judgment asymmetries for the four groups (original grouping). Left HFD and left neglect group had significantly greater asymmetry than the normal vision group, and a trend to be more asymmetric than the right HFD group.

	Right HFD	Left HFD	Left Neglect
NV	0.969	0.001*	0.003*
RHFD	-	0.026	0.019
LHFD	-	-	0.387

*Denotes significance after Bonferroni correction for 6 comparisons ($p<0.008$)

3.3.3 Reassignment of Left HFD Patients with History of Neglect

Since the findings of a smaller blind side threshold for the left HFD group was highly unexpected, explanations for this seemingly maladaptive behavior were explored. As residual neglect behaviors (not measurable on Line Bisection and Bells test) might still affect collision judgment behavior, the analysis was repeated grouping the left HFD patients with a self-reported history of left neglect on the study intake history (n=5) together with the

patients testing positive for neglect (n=5) (total n=10, see table 4). Two right HFD patients reported a history of right neglect but showed no asymmetry and so were not regrouped.

Table 4 summarizes the collision judgment measures after the regrouping. The remaining left HFDs not reporting a history of neglect (n = 8) no longer had a significant difference in blind and seeing side collision thresholds (Figure 10a) and no longer had significantly greater asymmetry than the NV group (table 5 and figure 10c), suggesting rightward maladaptive asymmetry was a subclinical manifestation of left neglect. By comparison, the new neglect-history group (including both those with a history and those testing positive) had significantly greater maladaptive asymmetry than all of the other groups (table 5 and figure 10c).

Table 4: Regrouping of patients with a history of left neglect. Values represent the median and interquartile ranges for the collision judgment measures by side of field loss and presence or history of left neglect.

Group		Blindside Threshold (cm)	Seeing Side Threshold (cm)	Asymmetry (Blind – Seeing) (cm)	Collision Envelope Width (Blind + Seeing) (cm)	Detection Failures
Normal	n=21	46 (39 to 58)	46 (39 to 53)	0.3 (-4 to 5.4)	86 (78 to 114)	0%
Right HFDs	n=11	42 (30 to 68)	46 (30 to 59)	-0.6 (16 to 11)	76 (66 to 137)	5% (0 to 13)
Left HFDs	n=8	37 (35 to 42)	44 (33 to 58)	-8 (-11 to 1)	80 (72 to 95)	4% (0 to 5)
Left Neglect History	n=10	28 (18 to 62)	59 (48 to 132)	-27 (-54 to -19)	91 (70 to 180)	16% (1 to 24)

Table 5: P-values for post hoc pairwise between-group comparisons of collision judgment asymmetries for the four groups after regrouping showing significant asymmetry of neglect-history group relative to the normal, right HFD, and left HFD.

K-W ($p<0.001$)	Right HFD (n=11)	Left HFD (n=8)	Neglect-History (n=10)
NV (n=21)	0.969	0.03	<0.001*
RHFD (n=11)	-	0.272	0.001*
LHFD (n=8)	-	-	0.006*

*Denotes significance after Bonferroni correction for 6 comparisons ($p<0.008$)

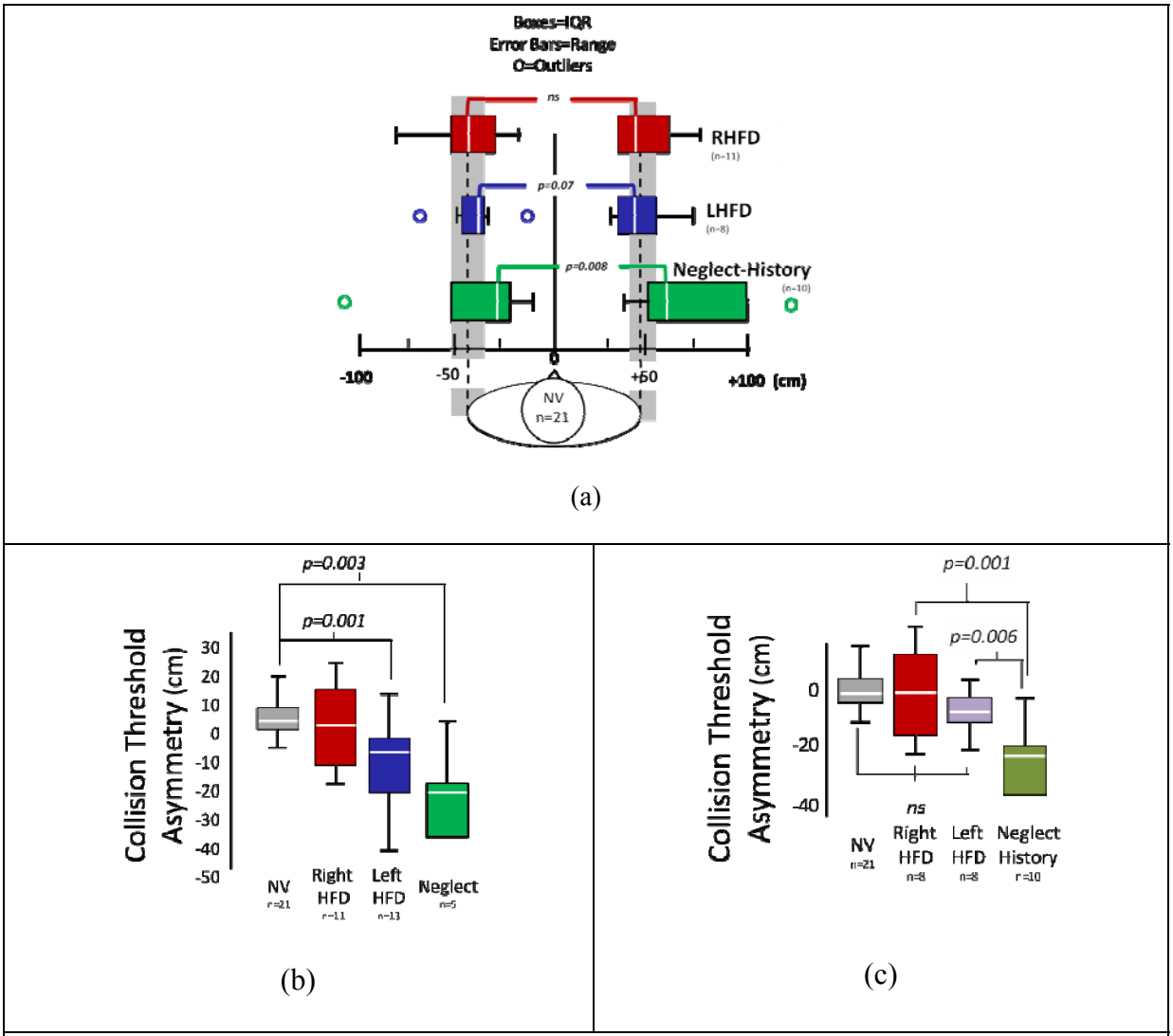


Figure 10: Boxplots of regrouped collision envelope, and original and regrouped between groups analyses. Asymmetry is eliminated from the left HFD group when reassigning patients with a self-reported history of left neglect into the neglect group (renamed neglect-history). a) Re-illustration of the collision envelope boxplots after regrouping showing the significant negative asymmetry of the neglect-history but not the left HFD group (compare against figure 9b). b) Original grouping illustrating between-groups comparisons with significant collision threshold asymmetry for both the left HFD and left neglect groups. c) Re-grouping illustrating significant asymmetry only for the neglect-history group.

3.3.4 Multiple Linear Regression Analysis

In addition to presence/history of neglect, it was possible that other factors such as age, duration of vision loss or the proportion of blind side detection failures might affect collision judgment behaviors. Therefore a forward step-wise linear regression analysis was performed with these factors as independent variables (listed in Table 6) and collision judgment asymmetry as the dependent variable. Neglect-history was the only factor that was selected as being predictive of collision threshold asymmetry, accounting for 36% of the variance (r^2 = 0.39, r^2[adj] = 0.36, n = 29, F(1, 22) = 14, p = 0.01), table 6.

Table 6. Results from forward step-wise multiple linear regression analysis for collision threshold asymmetry. The new grouping factor neglect-history (history of left neglect or tested positive for left neglect) was the only covariate selected as a predictor.

		Prediction Model					
		Unstandarized					
Dependent Variable	Independent Variable	B	SE	β	*t*	*p*	r^2
Asymmetry	(Constant)	-3.4	5.38		-0.63	0.54	0.39
	History of and test-positive Left Neglect (n=10)	-32.9	8.8	-0.62	-3.74	0.001*	
	Excluded Variables						
	Test-positive Left Hemispatial Neglect				0.58	0.57	
	Left HFD				-0.79	0.44	
	Proportion Blind Side Detection Failures				-0.05	0.96	
	Age				-0.88	0.39	
	Duration of Vision Loss				0.02	0.98	

3.4 Width of the Collision Envelope

Analysis of the overall width of the collision envelope (Absolute blind side threshold + seeing side threshold) revealed no significant between group differences (Kruskal-Wallis, old

grouping p=0.664, new grouping p=0.840; tables 3 and 5) suggesting a uniform rightward shift of the collision envelope in neglect-history patients.

3.5 Other Mobility Measures

3.5.1 Mobility Questionnaire

Mobility questionnaire data were available for 24 patients. A negative correlation would indicate that patients with a maladaptive (negative asymmetry) reported more difficulty with mobility. However, there were no significant correlations between collision judgment asymmetry and perceived difficulty with mobility (figure 11), either for all HFD participants together (n=24, Spearman's *rho*=0.01, p=0.485) or for each of the three groups (right HFD, n=9, *rho*=0.560, p=0.117; Left HFD n=7, *rho*=-0.367, p=0.418; Neglect-History n=8, *rho*=0.524, p=0.183).

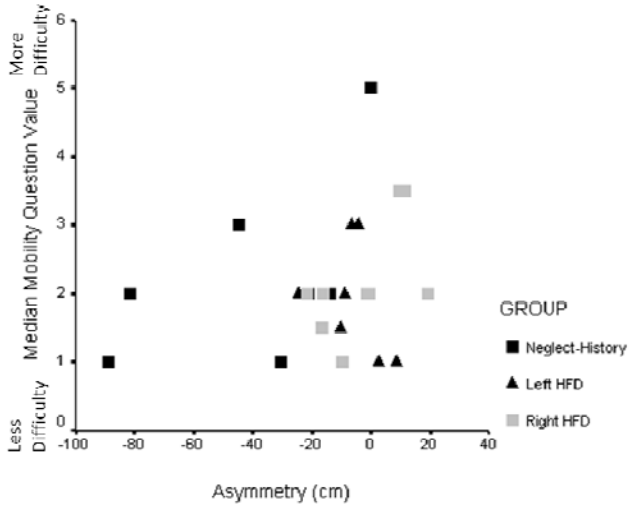


Figure 11: Median perceived difficulty with mobility plotted against collision judgment asymmetry. There was no significant relationship between these two variables.

3.5.2 Driving Simulator Lateral Lane Offset

Eight patients with right HFD, 2 with left HFD, and 7 with Neglect-History performed the driving simulator assessments. They showed significantly more lateral lane offset to the right (p=0.006, Mann-Whitney) than patients with right HFD (Neglect-History: median offset 43cm rightward (IQR 13 to 62); right HFD: -12cm leftward (IQR -17 to 18)), see figure 12. The magnitude of lane offset was not correlated with collision judgment asymmetry (Spearman *rho*=-0.336, *p*=0.187).

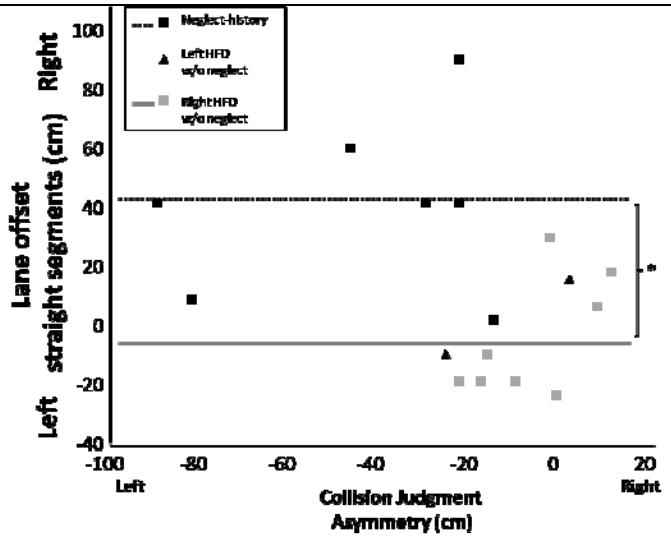


Figure 12: Lateral lane offset for straight segments plotted against the collision judgment asymmetry. The dashed line represents the median offset for patients with neglect-history who performed the driving simulator assessment, n=7. The solid line (gray) is the median offset for right HFDs, n=8. Only 2 patients with left HFD without neglect history performed the drive and so were not included in the analysis, but are plotted (triangles). While the rightward lane offset in patients with neglect history was significant, there was no significant correlation with the magnitude of collision asymmetry.
(*denotes p=0.006, Mann-Whitney)

3.5.3 Obstacle Course

Eight patients performed the obstacle course assessment right HFD (n=4), left HFD (n=2), neglect-history (n=2). Between groups comparisons were not performed due to the small sample sizes; however, correlations between asymmetry and obstacle course performance measures were evaluated. Although there was no significant correlation with the number of obstacle course collisions (*rho*=-0.331, p=0.423), there was a significant positive correlation with percent preferred walking speed (*rho*=0.738, p=0.04), figure 13. Higher values of percent preferred walking speed are an indicator of better mobility, so a positive correlation suggests that as maladaptive asymmetry increases, walking speed decreases.

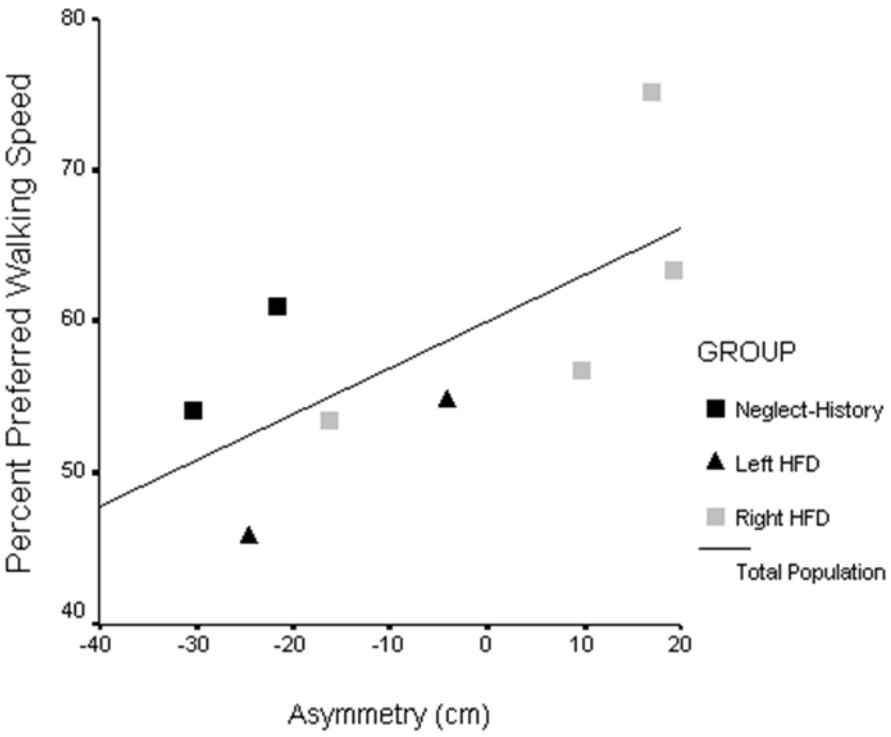


Figure 13: Collision judgment asymmetry plotted against percent preferred walking speed showing a significant correlation.

3.6 Schenkenberg Line Bisection and Collision Judgment Asymmetry

Line bisection data were available for 10 patients with right HFD, 8 with left HFD, and 10 with Neglect-History. There was no correlation between the mean line bisection error and the collision judgment asymmetry for any of the groups. However, patients with greater variability in performance on line bisection (SD) had significantly greater maladaptive asymmetry (Spearman's rho= -0.419, p=0.03), figure 14.

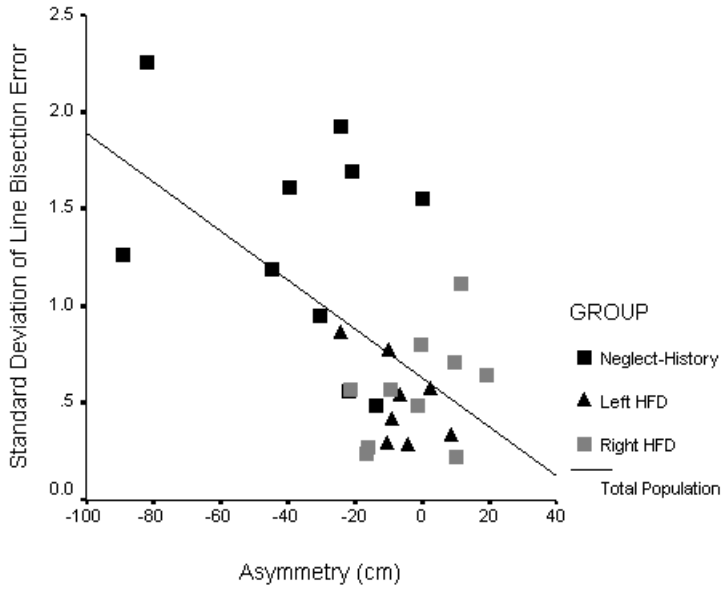


Figure 14: Line bisection standard deviation plotted against collision judgment asymmetry showing greater standard deviation in the Neglect-History group.

4.0 Discussion

The results of this study did not support our primary hypothesis that HFD patients without neglect would show an increased collision threshold on the blind side as a compensatory strategy or from a visuospatial disturbance. Rather, our data strongly suggest that right HFD

patients have symmetrical collision judgment thresholds (similar on the blind and seeing side), as do normally-sighted individuals. However, left HFD patients allowed obstacles to get closer to the path of virtual movement on their left (blind) compared to their right (seeing) side before reporting them as a collision hazard (fig 9b). This behavior was predicted for patients with left neglect, who often exhibit rightward deviations in line bisection(Schenkenberg et al., 1980) and in judgments of straight ahead,(Farne, Ponti & Ladavas, 1998, Heilman et al., 1983, Vallar, 1998) but it was unexpected in left HFD patients with a negative line bisection and bells test.

4.1 Subclinical Left Neglect Explains Asymmetry in the Left HFD Group

Differences in behavior between the right and left HFD groups could not be accounted for by differences in age, duration of vision impairment or mental status (as the two groups were very similar in all these characteristics), see table 1. However, when left HFD patients with a self-reported medical history of left neglect were regrouped with the patients that tested positive for left neglect, only a small and statistically non-significant amount of maladaptive asymmetry remained in the non-neglect left HFD group. By comparison, the new combined Neglect-History group had significantly greater maladaptive asymmetry than both the non-neglect left and right HFD groups (figure 10 and table 4). These findings suggest that residual subclinical left neglect (per the self-reported history) may still affect collision judgment behaviors, even though not measurable on standard paper and pencil neglect tests such as Line Bisection.

This is not the first study to report persistent neglect behaviors in seemingly recovered patients. For example, Buxbaum et al found that 47% of right brain-damaged patients exhibited chronic neglect behaviors on at least one of several neuropsychological tests (Buxbaum et al., 2004). Likewise, Goodale et al found persistent rightward reaching trajectories in recovered neglect patients (Goodale, Milner, Jakobson & Carey, 1990). My thesis experiment supports the opinion that clinical diagnosis of neglect and resultant management should rely on multiple tests targeting various functional and behavioral modalities. In patients with left HFD, it might be concluded from this data that a detailed history is more valuable than Line Bisection or Bells Testing.

4.2 Theories on the Mechanism of Rightward Collision Judgment Asymmetry

Right hemisphere damage might lead to the observed asymmetric judgments through 1) blindside detection failures, 2) cognitive and attentional disturbances, or 3) a rotational or translational shift in egocentric spatial maps.

Blind side Detection Failures Do Not Explain Asymmetry

Blindside detection failures were not significantly higher in the neglect group, and were not a significant predictor of asymmetry in the linear regression model (section 3.3.4). This has led to the conclusion that the asymmetry was not related to detection failures. Still, one limitation of this study was that it did not completely rule out the influence of detection failures, which might have been accomplished by repeating the trial as many times as necessary to get a collision judgment response.

Cognitive and Attentional Disturbances May Explain Asymmetry

Anosognosia, hypervigilance, and perseveration are cognitive and attentional disturbances associated with left neglect which may explain or contribute to the measured asymmetry.

Anosognosia, defined as a de-emphasis or poor awareness for left side physical impairments, is a hallmark behavior in left neglect (Cutting, 1978, Jehkonen, Laihosalo & Kettunen, 2006). Anosognosia might result in a decreased valuation (Sugrue, Corrado & Newsome, 2005) of all hazards but more so on the left, resulting in more risky behavior and therefore a smaller threshold on the left despite normal spatial perception.

Hypervigilance (pathologically heighted attention) for stimuli on the right is a behavior which has been described in some left neglect patients (Bartolomeo & Chokron, 1999) which may result in higher valuation of collision risk for obstacles on the right (seeing) side, increasing the threshold.

Perseveration, difficulty disengaging from a task or response which is typically worse on the ipsilesional side, is common in patients with left neglect (Kleinman, DuBois, Newhart & Hillis, 2013), and could contribute to asymmetry since it is typically much worse on the ipsilesional side. Perseveration may also lead to higher response variance, like that observed in the neglect group (figure 9b, figure 10a, in tables 2 and 4 see IQRs). However the protocol attempted to remediate this type of behavior when (after ~10 or more trials with the same response) the experimenter paused to reissue the instructions, confirm an understanding of the task, and confirm that indeed the patient felt the obstacle would have “collided with

their body" or "missed them entirely" (careful not to lead a particular response), see methods section 2.2.3. Despite this effort, it is still possible that some (but not all) of the sample had cognitive and/or attention disturbances contributing to the asymmetry.

Disordered Egocentric Spatial Maps May Explain Asymmetry

Egocentric perception can be thought of as a coordinate system used by the brain to monitor body position and its relationship to the external world. Multimodal sensory input from vision, proprioception, and vestibular is used to construct and maintain this perceptual representation.(Karnath, 1994a)

1) Rightward Rotation in Egocentric Spatial Maps: The Rotational Model

Sensory inputs for egocentric perception primarily provide angular information, which is related to their sensitivity around an axis of rotation (eyes, head, waist, semicircular canals). Therefore a rotational model of disturbed egocentric perception to explain the findings was desirable. The measured asymmetry in collision judgments might occur if proprioceptive misinformation suggests the torso is rotated rightward when it is actually in the neutral position. In such a situation the patient could misinterpret their path of movement in the walking simulator as angling to the right of the actual path (figure 15). Obstacles appearing on the left would be perceived as not posing a collision threat closer to the actual path of movement, resulting in the asymmetry observed.

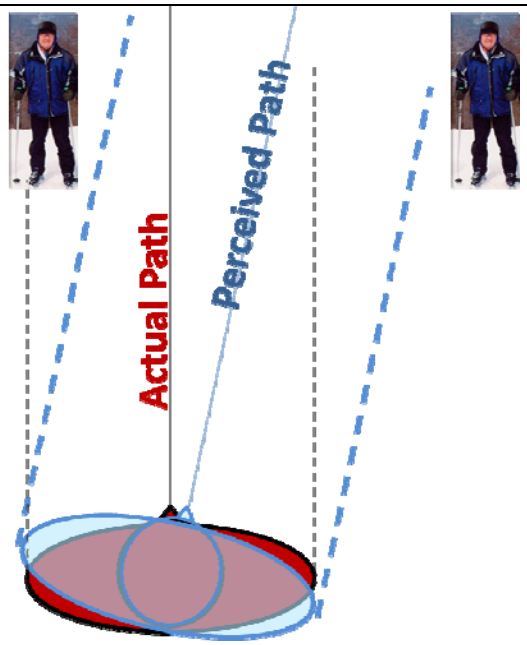


Figure 15: Illustration of a rightward rotation in egocentric perception of the torso leading to a smaller collision threshold on the left and larger on the right. The solid red underlying human figure represents the patient's actual body orientation, while the transparent blue human figure represents their perceived body orientation.

Rotational Model Cont'd

In actual walking or driving a wheelchair, this rotational model would predict that the patient, after visually identifying a goal, would rotate left to move towards the goal to align it with the perceived mid-sagittal axis (figure 16). Once moving, the error would become apparent as the perceived axis becomes misaligned from the goal. The patient would correct to the perceived axis (incorrectly), and the process would repeat, resulting in a curved trajectory similar to that reported by Rushton et al in response to base-right prisms (Rushton, Harris, Lloyd & Wann, 1998).

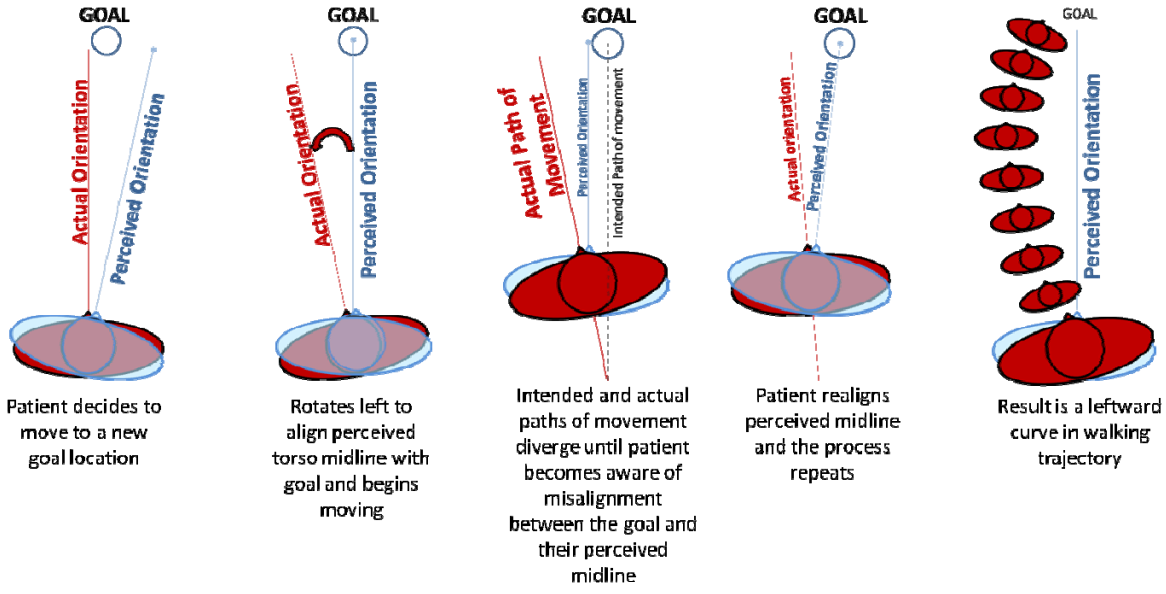
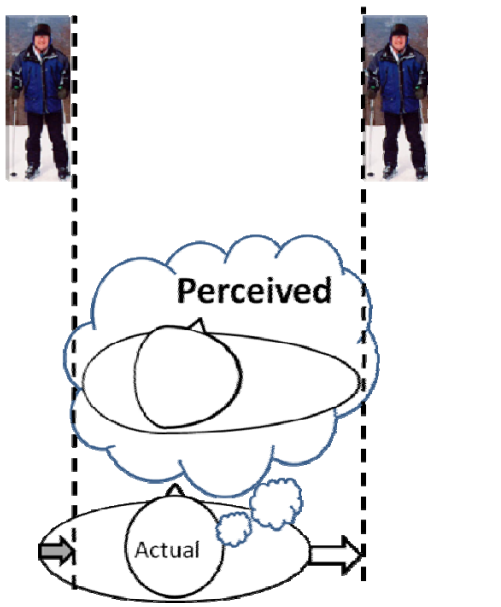


Figure 16: Illustration of the mobility behavior predicted by the rightward rotational model. The red human figure represents the actual body orientation whereas the transparent blue figure represents the perceived body orientation. The open circle represents a visually identified goal to which the patient intends to move towards.

2) Asymmetric Representation of Body Schema: Right Translational Shift Model

Damage to brain areas which receive proprioceptive signal for the left side of the body might result in the brain constructing an incorrect egocentric perception of body size such that the right side is "perceived" as being larger than the left (figure 17). This is similar in concept to what others have termed representational neglect.(Buxbaum et al., 2004) The result might be a rightward translational shift (rather than rotational) in the perceived body midline. During mobility, this model would predict a consistent leftward offset regardless

of distance to the goal. In passing through a doorway, the patient should pass more closely to the left side or even collide.



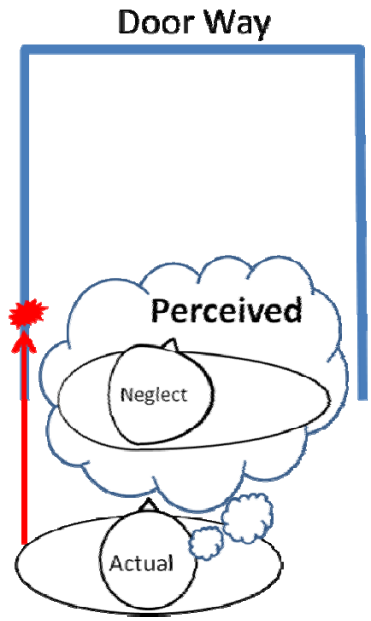


Figure 17: Illustration of a rightward translational shift from an asymmetric representation of the body schema resulting in a smaller threshold on the left and larger on the right.

3) Deviated Visual Maps (Visual Midline Shift)

It has been proposed that some patients with unilateral brain damage exhibit a shift in perceived visual midline, based on errors in judgment of straight ahead (Padula, 1998). If a patient reports that an object is straight ahead when it is actually to their right, this could suggest a leftward shift in visuotopic or spatiotopic coordinates (Figure18a). Similar to the other models this may be a representational error where visual space on the left is under-represented compared to the right. Since this representation of visual space is not

hinged to the position of the eye and its rotational axis, the shift may be translational. Alternatively this could be an error in the calibration between the felt position of the eyes/head and the torso, resulting in a rotational error. The result should be very similar to the misperception of torso alignment described above, and may even represent the same dysfunction.

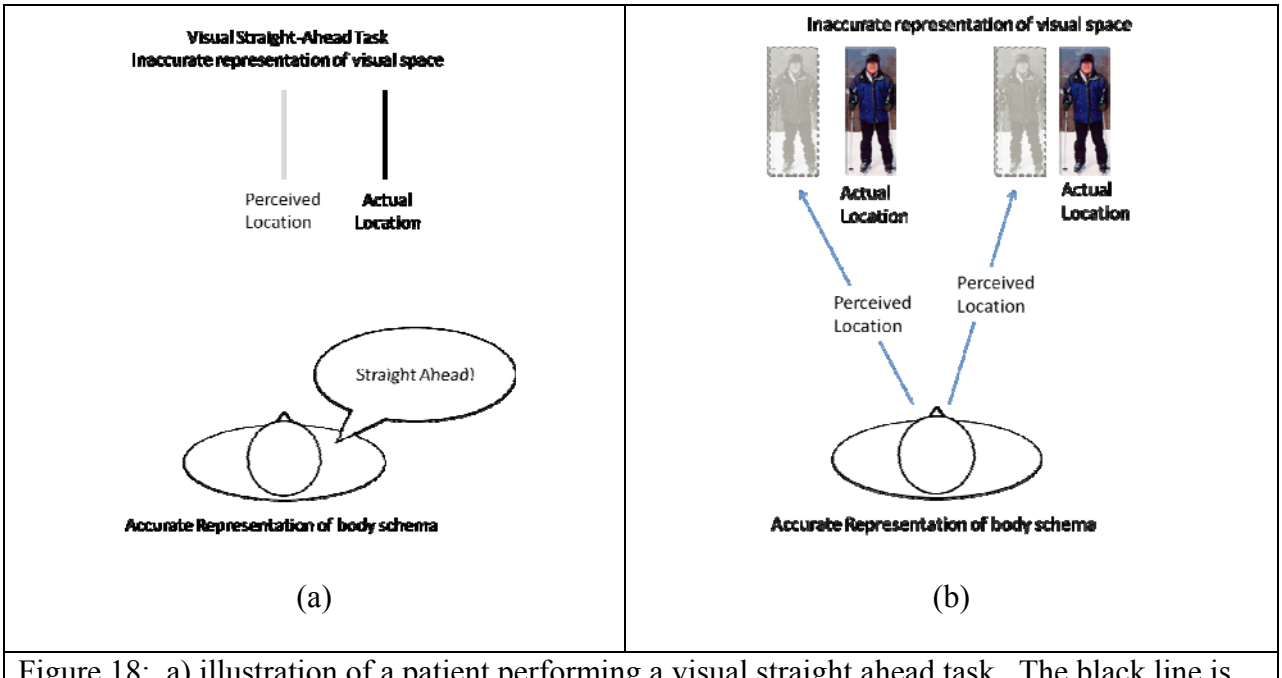


Figure 18: a) illustration of a patient performing a visual straight ahead task. The black line is moved slowly from left to right or right to left and the patient verbally reports when it is straight ahead. Patients with neglect make errors to the right, suggesting they perceive the line further to their left than it actually is (grey line). b) Illustration of the effect that a straight-ahead judgment error would have on the collision judgment task. Patients with a straight ahead error to the right should perceive the obstacle as being further from their path of motion on their left than it actually is. This is consistent with what was observed (larger threshold on the right side, smaller on the left).

4.3 Possible Treatments for Collision Judgment Asymmetry

A rightward deviation in egocentric perception, whether rotational or translational, may respond to treatment with base-left yoked prismatic lenses which deviate the visual field to the right (but do not deviate proprioceptive or vestibular information). Therefore if the visuotopic coordinates are normal/accurate but body schema derived from proprioceptive and vestibular information is rotated or translated rightward, the vision might be shifted right to match the disordered body schema. Conversely, a rightward shift in visuotopic maps (figure 18) might be corrected with a base-right yoked prism. Data (table 4) suggest the asymmetry is between 19cm and 54cm (median 27cm). Half of this (13.5cm) would need to be corrected (assuming a uniform rotation or shift) at an average virtual obstacle distance of 4m (median~2° shift, 4Δ); a reasonable amount optically and cosmetically. Where neurologically normal individuals rapidly adapt to yoked prisms, the Neglect-History patient would be brought into alignment and so would have no stimulus for adaptation and prolonged benefit might be achieved.

4.4 Relationship of Collision Judgment Asymmetry to Other Mobility Measures

Self-Reported Mobility Difficulty

There was no significant relationship between perceived difficulty with mobility and collision judgment asymmetry. Anosognosia in the Neglect-History group may have reduced the likelihood of finding a relationship as patients with anosognosia tend to under report impairments.

Driving Simulator Lateral Lane Position

Based on collision judgment data it would be predicted that the Neglect-History patients would allow less space between themselves and obstacles on their left side (Figures 15 and 17), and so they should have shown a leftward lane offset in the driving simulator. However, Neglect-History patients showed a highly significant rightward lane offset while the right HFD group were on average only slightly in the leftward direction, consistent with the prior study by Bowers et al. (Bowers et al., 2010), see figure 12 in section 3.5.2. If the visuotopic shift model was correct (figure 18) and the perceptual error resulted in a rightward average lane offset, the magnitude of the offset should have been correlated with magnitude of the collision judgment asymmetry. However, the lateral lane offset did not correlate with the magnitude (or direction) of the collision judgment asymmetry. Instead I propose that this lack of correlation reflects "collision judgment abandonment" and instead "deciding" to move as far to the right as the lane will allow. If in the months after the stroke, patients misjudge their body position and collide with obstacles, it would be reasonable to expect they would abandon using their collision judgment abilities and attempt to compensate by moving far to the right side. This is even more likely when there is the danger of oncoming traffic.

Obstacle Course

While the interpretation of the obstacle course data is limited by the small sample size, it seems to provide preliminary evidence that patients with collision judgment asymmetry had a greater reduction in walking speed in the obstacle course (compared to walking an

unobstructed path, ie. percent preferred walking speed) than patients with little to no collision judgment asymmetry, most likely representing a compensatory strategy. Increased collisions in those with large maladaptive collision asymmetries were not evident, which is consistent with the independent mobility status of our sample of patients.

Relationship of Collision Judgment Asymmetry to Line Bisection

Our data suggests the magnitude and direction of line bisection errors are not useful in predicting collision judgment asymmetry. If the rotational model is correct, the shorter working distance of line bisection (performed at ~0.5m) would render the line bisection test ~8 times less sensitive than the collision judgment task (performed at ~4m). Visual feedback during the line bisection task would also contribute to reduced sensitivity. Any proprioceptive misrepresentation of the arm position to the right could be corrected with visual feedback. Visual feedback was not readily available during collision judgment testing (arms were hidden under the table) and so errors are likely to be more pronounced.

There may still be some value to line bisection in predicting collision judgment asymmetry using the standard deviation of the bisection error. Greater variability (SD) in bisection performance was significantly correlated with greater collision judgment asymmetry (section 3.6, figure 14), which might reflect a generalized difficulty with spatial tasks.

4.5 Comparison of Results to Other Studies of Mobility in Left Neglect Patients

Prior studies looking at veering behavior in left neglect patients seem to contradict the driving simulator data. Turton et. al. and others found that patients drifted left when driving a wheelchair, and right when walking.(Turton et al., 2009) Differences in walking and wheelchair behavior might be related to the interaction of motor impairment and visual perception. For example, when driving a motorized wheelchair, the visual perceptual dysfunction is likely to be the primary influence on behavior (wheelchair was motorized and only required a small movement of the hand, minimizing the motor component).

So why then did our patients driving in the simulator not drift left like those driving wheelchairs in the Turton et. al study? This may be related to the heightened risk of oncoming traffic. Tasks with greater risk for injury (walking and driving) are more likely to evoke compensatory strategies to avoid collisions (moving right). This is the best explanation for the thesis population, since most were cognitively intact, adapted to their visual loss (mean years since onset of 6.7 years), and independently ambulating. Conversely Turton et. al.'s subjects were patients in an early post acute environment (mean time since stroke 39.7 days) who likely were unaware of their impairments (or less so), as is typical with this population of neglect patients, and so were unlikely to be strategically compensating. Since independent mobility is so important and neglect patients have more falls (Campbell & Matthews, 2010) and are frequently denied motorized wheelchairs for safety reasons (Dawson & Thornton, 2003), further research in this area is critical.

4.6 Collision Envelope Paradigm as an Outcome Measure for HFDs

When initiating this study, there was some concern that brain injured patients might not be able to reliably perform the collision judgment task. However, our results suggest that, as for normally sighted observers and patients with tunnel vision, collision judgment behaviors of HFD patients could be measured with the collision envelope paradigm and a Gaussian could be fitted to the data for each patient. Furthermore, statistically significant between-group differences in collision judgment asymmetry were found. However, the actual threshold measurement showed a relatively poor coefficient of repeatability. In order to use this paradigm to as an outcome measure to evaluate the efficacy of interventions, improvements in the paradigm are necessary. Implementing an algorithm using a Bayesian adaptive estimation method, as has been used previously for contrast sensitivity testing (Lesmes, Lu, Baek & Albright, 2010), might be utilized to target the threshold region and perhaps improve repeatability while decreasing testing time.

4.7 Conclusions

This is the first study to evaluate collision judgment behaviors of HFD patients using the collision envelope paradigm. Our sample was representative of patients reporting to vision rehabilitation clinics. Results suggest that left HFD patients with a history of or current diagnosis of left neglect allow obstacles to get closer on their blind side before judging them as a collision risk during virtual walking. This misjudgment is unrelated to detection of the obstacle. Specifically, the patients see the obstacle, but misjudge its location relative to their body/path of motion. This most likely represents a rightward rotation or deviation in

egocentric localization as has been measured in left neglect, with cognitive and attentional disturbances potentially contributing in some patients. Data from the driving simulator and obstacle course provide preliminary support for the conclusion that the collision judgment asymmetries measured in the walking simulator are relevant during real world mobility. Patients seem to compensate for their spatial dysfunction by moving far to the right and slowing down.

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Appendix A: Mobility Questionnaire

Read the questions and response options. Circle responses

I am going to ask you to rate the level of difficulty you have experienced in certain situations when walking or moving in your wheel chair without the aid of a companion.

How much difficulty did you have: (N/A = not applicable)

1. Moving about at home?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
2. Moving about at work/school?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
3. Moving about in stores?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
4. Moving about outdoors?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
5. Moving in familiar areas?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
6. Moving in unfamiliar areas?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
7. Moving about in crowded situations?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
8. Walking up steps / stepping onto curbs?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
9. Walking down steps / stepping off curbs?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
10. Noticing objects off to the side?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme
11. Avoiding bumping into obstacles (including people)?	**0** N/A **1** No difficulty **2** A little **3** Some **4** Moderate **5** Extreme