A hit-and-miss investigation of asymmetries in wheelchair navigation

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In contrast to the leftward inattention caused by right parietal damage, normal brain function shows a subtle neglect of the right and left sides in peripersonal and extrapersonal space, respectively. This study explored how these attentional biases cause healthy individuals to collide with objects on the right. In Experiment 1, participants navigated manual and electric wheelchairs through a narrow doorway. More rightward collisions were observed for the electric, but not the manual, wheelchair. Experiment 2 demonstrated that the rightward deviation for electric wheelchairs increased for wider doorways. Experiment 3 established that the rightward deviation is not the result of task-related vestibular input, using a remote control device to operate the wheelchair. The rightward deviation persisted in Experiment 4 when the doorway was removed, suggesting that the bias is the result of a mis-bisection of space. In Experiment 5, the rightward bias was replicated using an electric scooter, which is steered using handlebars. Finally, Experiment 6 required participants to point to the middle of the doorway, using a laser, before moving the scooter. Rightward mis-bisection was observed in both conditions. Rightward mis-bisection of lines in extrapersonal space provides the most parsimonious explanation of the rightward collisions and deviations.

As we move through and interact with the environment, it would seem reasonable to expect that objects or events on the left or right sides of space are equally likely to attract our attention. Contrary to this expectation, research suggests that the amount of attention devoted to the left and right hemispaces is asymmetrical. What is more, these asymmetries of attention change as a function of the distance between the observer and the object or event.

For objects located within a person's reach (peripersonal space), a leftward bias of attention in the general population is often observed. This leftward bias of attention can be demonstrated using line bisection tasks, in which participants mark the midpoint of a horizontal line that extends from left to right. Instead of placing the bisector

around the true middle, participants reliably place the mark slightly to the left of true center (Jewell & McCourt, 2000; McCourt, 2001). Overestimation of the leftward features of a stimulus has also been observed for judgments of luminosity (Nicholls, Bradshaw, & Mattingley, 1999; Tomer, 2008), numerosity (Luh, 1995), size (Nicholls et al., 1999), and the perception of chimeric faces (Coolican, Eskes, McMullen, & Lecky, 2008). The leftward bias extends beyond physical stimuli and occurs for mental representations of lines, such as mental alphabet lines (Nicholls & Loftus, 2007) and mental number lines (Loftus, Nicholls, Mattingley, & Bradshaw, 2008). The bias is therefore the result of a higher order attentional bias in spatial cognition, rather than a low-level perceptual asymmetry.

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Objects located outside a person's reach (extrapersonal space) are thought to be coded by different cognitive and neural mechanisms (Weiss et al., 2000). For example, Committeri et al. (2007) demonstrated a dissociation between extrapersonal and peripersonal space in a group of right ischaemic patients. Attention within extrapersonal space was based on the integrity of a ventral circuit including the right frontal and superior temporal regions. In contrast, attention in peripersonal space was associated with a dorsal circuit that coded proprioceptive and somatosensory inputs, including the right inferior parietal regions (see also Butler, Eskes, & Vandorpe, 2003). Research using transcranial magnetic stimulation has indicated that similar neural circuits are used in the intact brain (Bjoertomt, Cowey, & Walsh, 2002). Behavioral research carried out by Longo and Lourenco (2006) indicated a behavioral dissociation in the general population. They asked participants to bisect a line, using a laser pointer. A leftward bisection bias was observed when the line was in peripersonal space, which reversed to a rightward bisection bias when the line was placed in extrapersonal space. Interestingly, the rightward bias in extrapersonal space was eliminated if participants used a stick to make the bisection. The stick presumably acted as an extension of the arm and brought the object within "reach" and, therefore, peripersonal space. A change in line bisection as a function of viewing distance has been reported by other researchers (e.g., Gamberini, Seraglia, & Priftis, 2008; McCourt & Garlinghouse, 2000), although this effect is not universal (Cowey, Small, & Ellis, 1999).

The biases of attention in individuals with an intact brain share similarities with the neurological symptoms of neglect following right parietal damage, which is typified by an inability to orient toward, explore, and respond to stimuli located in the contralesional space (Heilman, Watson, & Valenstein, 1993). For this reason, the attentional asymmetries that occur in the general population are often referred to as *pseudoneglect* (Bowers & Heilman, 1980). The analogy between neglect and pseudoneglect seems apt, given that both phenomena are affected in similar ways by stimulus modifications such as line length and width (McCourt & Jewell, 1999) and prismatic adaptation (Loftus, Vijayakumar, & Nicholls, 2009). The behavioral dissociation observed between extrapersonal and peripersonal space for pseudoneglect is also observed in neglect (Halligan & Marshall, 1991; Keller, Schindler, Kerkhoff, von Rosen, & Golz, 2005). Furthermore, the neural centers that give rise to pseudoneglect are homologous to those implicated in the manifestation of neglect, including centers located in the right posterior parietal cortex (Bjoertomt et al., 2002; Foxe, McCourt, & Javitt, 2003; Waberski et al., 2008). Thus, although it does not necessarily follow that attentional bias in the general population will mirror the bias shown by neglect patients, it seems that a shared asymmetry in the cognitive/neural basis of attention leads to a correspondence in this case.

Neurological and cognitive models of pseudoneglect frequently draw on models that have been used to explain the clinical syndrome of neglect. In line with this tradition, a recent model proposed by Siman-Tov et al. (2007)

explains pseudoneglect in terms of attention-facilitated processing of stimuli located in the left visual field. Like many neurological models of attention (e.g., Corbetta, Miezin, Shulman, & Petersen, 1993), Siman-Tov et al. proposed that the right hemisphere plays a dominant role in attention and attends to stimuli located in the left and right visual fields. More unusually, they found that the left hemisphere was also able to attend to both visual fields, albeit in a reduced capacity, as compared with the right hemisphere. The leftward attentional advantage in pseudoneglect was thought to be driven by two separate neurological asymmetries. First, it is driven by the dominance of the right hemisphere for spatial attention and its strong connection with the contralateral (left) visual field. Second, pseudoneglect is driven by an asymmetry in interhemispheric transfer, which favors the passage of information from the right to the left hemisphere (see Barnett & Corballis, 2005). The right hemisphere is therefore able to exert further control in the left visual field by influencing the left hemisphere via the strong right-to-left interhemispheric connection. One of the main advantages of the model proposed by Siman-Tov et al. is that, in addition to explaining the rightward attentional bias in neglect, it explains the leftward attentional bias in pseudoneglect. One shortcoming of this model and all other models of pseudoneglect is that they do not explain the rightward bisection bias that occurs in extrapersonal space. Although Siman-Tov et al. stated that ventral and dorsal circuits played a role in their model, it is possible that changes in the reliance on ventral and dorsal attentional circuits as a function of peripersonal and extrapersonal space (Bjoertomt et al., 2002) affect the pattern of information flow between the hemispheres and the visual fields.

Asymmetries in attention have the potential to affect the way we interact with the environment, particularly as we navigate our way through it. Salient examples of this impact come from the neglect literature, which has reported an increased frequency of collisions, particularly to the left. When confined to a wheelchair, patients with unilateral neglect are more likely to collide with leftward objects (Webster, Rapport, Godlewski, & Abadee, 1994; Webster et al., 1995), although leftward collisions may be diminished for wider doorways (Punt, Kitadono, Hulleman, Humphreys, & Riddoch, 2008). Turton et al. (2009) reported a dissociation between walking and wheelchair navigation in 15 left-sided neglect patients. When navigating a wheelchair along a corridor, the patients consistently veered to the left, whereas when walking, they veered to the right. A rightward deviation when walking through a doorway has also been reported by Robertson, Tegnér, Goodrich, and Wilson (1994). In contrast, Tromp, Dinkla, and Mulder (1995) found that patients with mild symptoms of neglect were more likely to collide with the left side of a doorway. It would therefore appear that the direction of the deviation when one is walking is less clear than when one is in a wheelchair. This dissociation might be related to differences in the amount of movement required and the effects of hemiplegia. Alternatively, walking might be particularly susceptible to the use of strategies, such as

patients' placing their hand on the right side of a corridor as they walk down it.

If neglect patients experience asymmetrical collisions or deviations, an asymmetry might also be expected in the general population due to pseudoneglect. Initial support for this idea comes from a study conducted by Turnbull and McGeorge (1998). They asked university students to recall whether they had collided with anything on their left or right side. Although more collisions were recalled on the right, this failed to reach statistical significance. There was, however, a significant relationship between the side on which the collision occurred and biases in line bisection performance, suggesting that bumping was related to pseudoneglect. To see whether the rightward collisions could be replicated under laboratory conditions, Nicholls, Loftus, Mayer, and Mattingley (2007) asked 276 students to walk through a doorway that was only marginally wider than the participants. To investigate the effect of unilateral hemispheric activation, the participants used their left, right, or both hands to fire a toy gun at a target as they passed through the doorway. Consistent with the operation of pseudoneglect, more rightward collisions were reported in the baseline condition, in which both hands were moving. Unilateral movement of the left hand, which increased activation in the right hemisphere, exacerbated rightward collisions. In contrast, movement of the right hand—hence, activation of the left hemisphere—caused more leftward collisions. In a follow-up study, Nicholls, Loftus, Orr, and Barre (2008) replaced the toy gun with a mobile phone and asked participants to enter numbers with the left, right, or both hands as they walked through the door. Once again, more bumps to the right were observed. In this case, however, the asymmetry in bumping was not affected by unimanual activity. To investigate the relationship between the bumping asymmetry and more traditional measures of pseudoneglect, a line bisection task was also administered. As in Turnbull and McGeorge, there was a correlation between bumping and line bisection, whereby individuals who bumped more often to the right also had a larger leftward bias for line bisection (and vice versa for individuals who bumped to the left).

Although the literature to date appears to show that the general population deviates or bumps to the right, a few important issues need to be resolved. Foremost among these is the issue of how pseudoneglect, or some other attentional mechanism, may bring about rightward collisions or deviations. In the collision studies carried out by Nicholls et al. (2007; Nicholls et al., 2008), it is possible that participants mentally marked the "center" of the doorway and then headed toward this point. In support of this, it has been demonstrated that neglect patients walk toward a point established early in the trajectory, with little or no updating during transit (Berti et al., 2002). Given that the doorway used by Nicholls et al. (2007; Nicholls et al., 2008) was at least 2 m away and, therefore, in extrapersonal space, the bisection should have been placed slightly to the right of true center. If the participants headed toward this point, rightward collisions and deviations would be expected.

Rightward deviations or bumping could also be related to attentional capture or a failure to disengage from one

side of the doorway. It is possible that neglect patients fail to attend to the left and deviate in this direction because attention is captured by the right doorpost (for a discussion, see Robertson et al., 1994). This asymmetry in behavior could be related to the *disengagement deficit* in neglect patients (Posner, Walker, Friedrich, & Rafal, 1987). The deficit relates to a disproportional difficulty in shifting attention from cues in the right (ipsilesional) hemisphere to targets located in left (contralesional) hemisphere (see also Rastelli, Funes, Lupiáñez, Duret, & Bartolomeo, 2008). Although the pattern of results associated with a disengagement deficit is clear, the nature of the mechanisms that underlie the deficit is less obvious. Cohen, Romero, Servan-Schreiber, and Farah (1994) suggested that the deficit associated with disengagement in parietal patients need not involve a specific *disengage* mechanism and that the phenomenon could be an emergent property of a damaged attentional network. This proposition was supported by Vecera and Flevaris (2005), who investigated the effect of data- and goal-driven mechanisms on disengagement in an undergraduate population.

Consistent with the effect of pseudoneglect, studies in the general population have shown a difficulty in disengaging attention from the left visual field to the right visual field. For example, Okada, Sato, and Toichi (2006) presented valid and invalid cues to the left and right visual fields prior to the presentation of a lateralized target. The slowest reactions were observed when the cue was presented to the left visual field and the target appeared in the right visual field. Similar results have been reported for control subjects in a study of obsessive-compulsive disorder (Maril, Hermesh, Gross-Isseroff, & Tomer, 2007) and under high-load conditions using a central cuing paradigm (Evert, McGlinchey-Berroth, Verfaellie, & Milberg, 2003). Although a difficulty in disengaging attention from the left visual field has not always been found (Greene et al., 2008), it is possible that a subtle form of disengagement deficit operates in the general population whereby the left doorpost captures attention, causing the right side of the door to be partly ignored, leading to rightward deviations and collisions.

A second issue that needs to be addressed is the means of navigation. To date, most of the research investigating asymmetries in navigation in the general population has focused on ambulatory tasks. The present study extended this research to the operation of wheelchairs. There are a number of reasons why it was important to do this. First, besides walking, there are many other navigation tasks that require judgments of left and right, such as driving a car, sailing a boat, or flying a plane. For these tasks, small deviations to the left or right when a narrow passage is navigated can have dramatic effects. The operation of a wheelchair provides a good analogy to asymmetries in navigation that may occur in the operation of machinery. The advantage of wheelchairs is that they are small, can be operated in a laboratory, and can be operated symmetrically (unlike a car with a left- or right-hand drive). Second, because clinical neglect patients are frequently confined to a wheelchair, there is a clinical body of research with which our data can be compared. Third, the

operation of a wheelchair employs different efferent and afferent mechanisms, as compared with walking. Thus, walking through a doorway uses most of the major muscle groups in the body and requires considerable activation and control from the cerebellum and cerebrum (Joseph, 1985). In contrast, operating a wheelchair, especially an electric wheelchair, can minimize movements to just the fingers. Differences in the extent of motor activity may explain the dissociation between walking and wheelchair navigation in neglect patients (Turton et al., 2009). In addition, although both walking and wheelchair navigation involve input from the visual, auditory, proprioceptive, and vestibular systems, wheelchairs provide the opportunity to manipulate the input from these systems. Finally, Boyadjian, Marin, and Danion (1999) have suggested that veering¹ is the result of a peripheral mechanism related to differences in the forces applied by the left and right legs. Thus, wheelchairs allow us to rule out the possibility that the rightward bias observed by Nicholls et al. (2007; Nicholls et al., 2008) is the result of an asymmetry in the motion of the legs.

The present set of experiments therefore improved and expanded on previous research by using a variety of different wheelchairs and electric scooters to investigate rightward deviations and collisions in navigation. By manipulating the motor, sensory, and attentional demands of the task, we hoped to gain a better understanding of the cognitive and neural mechanisms that underlie asymmetries in navigation.

EXPERIMENT 1

The first experiment determined whether asymmetries in collisions can be observed during the operation of manual and electric wheelchairs. Participants passed through a doorway that was only slightly wider than the wheelchair, using electric and manual wheelchairs. Trials were scored according to whether the wheelchair hit the left side, right side, both sides, or neither side of the doorway.

If the predominance of rightward collisions observed by Nicholls et al. (2007; Nicholls et al., 2008) during walking is the result of an attentional bias, more rightward collisions should be observed for wheelchair operation. If the asymmetry in collisions did not generalize to the wheelchair task, it would suggest that rightward collisions while one is walking may be related to a motor asymmetry between the legs (Boyadjian et al., 1999) or to the effect of proprioceptive feedback from the muscles in the legs.

The manual wheelchair involves considerable motor output from the left and right arms and, hence, activation of the left and right cerebral hemispheres. In contrast, the electric wheelchair is a more perceptual version of the task and requires minimal movements. Although more rightward collisions were expected for both types of wheelchair, it is possible that asymmetries in the strength between the hands and/or asymmetries in hemispheric activation will eliminate or reduce the asymmetry for the manual wheelchair. In the case of asymmetries in strength, a stronger right hand may cause the right wheel to spin

more than the left, causing the wheelchair to veer to the left. Hemispheric activation is thought to be an important component of attentional asymmetries (Kinsbourne, 1993) and is known to affect asymmetries in collisions when one is walking (Nicholls et al., 2007). Large movements of the hands for the manual wheelchair may, therefore, cause significant bilateral activation of the hemispheres, which overrides any asymmetry related to pseudoneglect.

To investigate the effect of practice on collision asymmetries and to gauge test–retest reliability, the blocks were split into two halves during the analysis. As participants became more practiced, it was possible that the predominance of rightward collisions would subside. In addition, if wheelchair collisions are a reliable trait, asymmetries observed in the first half of the block should be related to the asymmetries observed in the second half.

Method

Participants. Undergraduate students ($n = 18$; 10 of them female and 8 male) with a modal age of 18 years participated in this study as part of their course requirements. A handedness questionnaire (Oldfield, 1971), which gives scores ranging from -10 (*completely left-handed*) to $+10$ (*completely right-handed*) indicated that all the participants were right-handed ($\bar{x} = +8$). The participants had normal or corrected-to-normal visual acuity and had normal movement in both arms. The project was approved by the Human Research Ethics Committee at the University of Melbourne. All the participants gave informed consent prior to the study but were naive in relation to the specific aims of the experiment.

Apparatus. A “doorway” was created by suspending two poles made of 19-mm dowel from a horizontal bar located 2.0 m above the floor. The vertical poles were attached to the horizontal pole using cup hooks, which allowed them to swing freely. The width of the doorway was set at 840 mm. To create the impression of an aperture in a solid frame, black cloth was attached between the vertical poles and the outer edge of the frame (see Figure 1). A manual and an electric wheelchair were used. The manual wheelchair was the standard type (Guardian, Easy Care 3000 Lightweight Wheelchair) operated using the hands to spin the rims on the wheels. The electric wheelchair (A&J Mobility Solutions, Model AJM FS110A) was operated using a joystick, where movements of the joystick resulted in movements in the corresponding direction of the wheelchair. The joystick was secured above the participants’ laps, along their midlines. To standardize the widths of the wheelchairs and to make sure that the participants’ hands did not touch the doorway when operating the manual wheelchair, an 840-mm length of wood (40 mm wide $\times$ 25 mm thick) was secured to the wheelchair over the participants’ laps. The wood did not interfere with the operation of the electric or the manual wheelchair. The width of the wood matched the width of the doorway (840 mm), making it extremely difficult to pass through the door without hitting one side or the other. The task was made deliberately difficult because trials on which neither side was hit would yield no data relating to asymmetries in navigation. The wood extended equally from the left and right sides of the manual and electric wheelchairs by 100 and 120 mm, respectively.

Procedure. At the start of each trial, the front wheels of the wheelchair were placed on a line on the floor, which ran parallel 2.5 m in front of the door frame. The center of the wheelchair was aligned with the center of the aperture. The participants were asked to move themselves in the wheelchair to a line that was placed 2.5 m behind the aperture without touching the sides of the “doorway.” They were encouraged to operate the wheelchair at a normal walking pace. For the manual wheelchair, the left and right hands were used to turn the respective wheels on the wheelchair. For the electric wheelchair, the joystick was mounted in front of the participants, along their midlines (i.e., above their laps). The participants used

Figure 1. Illustration of the doorway and wheelchair setup.

both hands to manipulate the joystick mechanism. Bimanual operation was used for both types of wheelchairs because of reports that unimanual activity can affect attentional asymmetries (McCourt, Freeman, Tahmahkera-Stevens, & Chaussee, 2001).

An observer, blind to the aims of the experiment, recorded whether the wheelchair, or the piece of wood attached to it, hit the left side, right side, both sides, or neither side of the aperture. Only one type of response was collected for each trial. The experimenter stood immediately behind the wheelchair's starting position. When the participants reached the target, they maneuvered the wheelchair back to the starting point by going either clockwise or counterclockwise around the doorway frame. The direction in which they returned was alternated between trials. The room and floor were cleared to remove any stimuli that could be used to define the center of the aperture. The participants completed 20 trials using the manual wheelchair and 20 trials using the electric wheelchair. The order in which the wheelchairs were used was blocked and counterbalanced between participants. Prior to experimentation, the participants completed at least 5 practice trials with each wheelchair to ensure that they were familiar with its operation.

Results and Discussion

The average frequency of bumps for the manual and electric wheelchairs, across each of the response categories (right, left, both, and neither) is shown in Figure 2. Chi-square tests demonstrated that there were more right-side than left-side collisions [$\chi^2(1) = 31.7, p < .001$], more left-side than both-side collisions [$\chi^2(1) = 42.1, p < .001$], and more both-side than neither-side collisions [$\chi^2(1) = 96.8, p < .001$]. The increased frequency of rightward bumps, relative to leftward bumps, replicates the rightward asymmetry in walking collisions observed

by Nicholls et al. (2007; Nicholls et al., 2008). The low number of *neither* trials, where neither side of the doorway was hit ($<2\%$), demonstrates that it was almost impossible to move the wheelchair through the door without hitting at least one side of the doorway. For cases in which the participants missed hitting the doorway, it is possible that they went through at a slight angle.

Figure 2 also shows signs of an interaction between the number of left and right collisions and the type of wheelchair. To analyze this effect and to examine the effect of practice, a measure of asymmetry in collisions was calculated by subtracting the number of leftward collisions from the number of rightward collisions and then converting the result to a percentage of the total number of trials in that condition. Scores therefore ranged from -100 (100% leftward collisions) to $+100$ (100% rightward collisions). Scores approaching zero indicate no asymmetry in bumping. This measure of percentage asymmetry in collisions is similar to measures of bisection bias frequently used in line bisection studies (see Nicholls & Roberts, 2002). To examine the effect of time and practice, data from the manual and electric wheelchairs were split into two blocks. The first block contained the first 10 trials from a session, whereas the second block contained the last 10 trials. The data were analyzed with an ANOVA with wheelchair (manual, electric) and block (first, second) as within-participants factors. Effect sizes are expressed as partial eta-squared values. As can be seen in Figure 3, there was a main effect of wheelchair, whereby the rightward asymmetry in collisions was stronger for the electric wheelchair than for the manual wheelchair [$F(1,17) = 9.92, p < .01, \eta^2 = .843$]. To examine whether the collision asymmetries were significantly different from zero, one-sample t tests were used. The rightward collision asymmetry was significant for the electric wheelchair [$t(17) = 4.14, p < .001$], but not for the manual wheelchair [$t(17) < 1$]. The manual wheelchair required large movements of the hands, arms, and shoulders. As was outlined in the introduction, asymmetries in strength between the hands, or the effect of bilateral hemispheric activation,

Figure 2. Mean number of cases in which participants hit on the right side, left side, both sides, or neither side for the manual and electric wheelchairs ($\pm SE$ bars are shown).

Figure 3. Mean bumping bias for the manual and electric wheelchairs for the first and second halves of testing ($\pm$ SE bars are shown). Positive and negative values indicate a bias toward bumping to the right and left, respectively.

could account for the lack of a rightward bumping bias for the manual wheelchair. The rightward asymmetry in collisions observed for the electric wheelchair demonstrates that asymmetries in bumping occur when movements are minimized. The collision asymmetry therefore appears to be perceptual/attentional in origin and is not the result of asymmetries in movement between the legs (Boyadjian et al., 1999).

Because there was no effect of block [$F(1,17) < 1$], it appears that practice did not affect the rightward asymmetry in collisions. The effect of practice on the collision asymmetry was also consistent for both types of wheelchairs [$F(1,17) < 1$]. Correlations between the blocks revealed that the direction and strength of the collision asymmetry were reliable for the manual wheelchair [$r(18) = .58, p < .05$]. This reliability could be related to the relative strength of the left and right hands/arms. For the electric wheelchair, the reliability between blocks approached but did not reach statistical significance [$r(18) = .40, p < .1$]. The r value (.4) is of a moderate size, and it is likely that a significant correlation would have emerged if the sample size had been larger. The data therefore provide some support for the notion that collision asymmetries in the electric wheelchair are a reliable trait within individuals.

EXPERIMENT 2

The second experiment examined the generality of the effect observed in the first experiment. It is possible that the rightward collisions observed in the first experiment were the result of an asymmetry in the mechanics of the wheelchair, which caused it to veer to the right. To exclude this possibility, a different make and model electric wheelchair was used. Whereas in the first experiment, collisions

to the left or right were counted, in the second experiment, the position of the center of the wheelchair relative to the center of the doorway was measured. If participants collide more often to the right, they should also deviate to the right. This new measure of deviation allowed us to examine the effect of different doorway widths. For line bisection tasks, increases in line length are usually associated with larger leftward bisections (McCourt & Jewell, 1999). Although studies of lines in extrapersonal space vary the length of lines, they frequently collapse across this factor in the analysis (Longo & Lourenco, 2006; Lourenco & Longo, 2009). Despite this, if the bisection of extrapersonal space operates in a manner that is analogous to that for near space, one might expect the rightward deviation to increase with increases in door width.

To investigate the association between deviations in wheelchair navigation and more traditional measures of neglect, a line bisection task was also administered. Nicholls et al. (2008) observed that individuals who bumped to the right more often also had stronger leftward line bisection biases (and vice versa for individuals who bumped to the left). We therefore predicted that asymmetries in wheelchair navigation would be inversely correlated with line bisection biases.

Method

Participants. Sixteen right-handed ($\bar{x} = +9$) undergraduate students (10 of them female, 6 male) participated in this experiment. All other characteristics were the same as those described in the first experiment.

Apparatus. A doorway was created using the equipment described in the first experiment. The electric wheelchair used in this experiment was essentially the same as the one used in the first experiment, but was a different model (Glide Rehabilitation Products, Series 4). Once again, the wheelchair was operated using a centrally mounted joystick. The widest point of the wheelchair was 600 mm at the back wheels. A thin white line was placed down the back of the wheelchair to mark the middle. A digital video camera was placed immediately behind the wheelchair at its starting position and in line with the center of the aperture.

Procedure. At the start of each trial, the front wheels of the wheelchair were placed on a line on the floor, which ran 2.5 m in front of the door frame. The center of the wheelchair was aligned with the center of the aperture. The participants were asked to move themselves and the wheelchair to a line that was placed 2.5 m behind the aperture. They were asked to operate the wheelchair at a normal walking pace and were told to aim for the middle of the door. The joystick was held and operated using both hands. When the wheelchair passed through the doorway, it activated an LED, and the video camera recorded the position of the chair. When the participants reached the target, they maneuvered the wheelchair back to the starting point by reversing the wheelchair back through the doorway. The room and floor were cleared to remove any stimuli that could be used to define the center of the aperture. The participants completed 45 trials broken into three blocks of 15 trials. Three doorway widths were used (620, 750, and 1,100 mm), and these were varied between blocks, with the order counterbalanced between participants. Prior to experimentation, the participants completed at least 5 practice trials with the wheelchair to ensure that they were familiar with its operation.

Digital video recordings were analyzed on a laptop computer using GIMP software. The position of the white line on the back of the wheelchair was measured relative to the left and right sides of the doorway. Measurements were made in pixels and then converted to millimeters scaled to the actual size of the doorway. The zero point

of the scale was located in the center of the doorway, with negative and positive values reflecting deviations to the left and right, respectively.

The participants bisected 16 lines. The lines were printed one per page in black on a white A4 page. The lines, which were either 80 or 120 mm long and 2 mm thick, were offset at random from the vertical center of the A4 sheet. The participants bisected the lines using a pen with their left or right hands. Half of the participants bisected the first 8 lines with their left hands and swapped hands for the last 8 lines (and vice versa for the other half). Bisections were scored by the experimenter to the nearest 0.5 mm. Negative and positive values indicate that bisections were placed to the left and right of center, respectively.

Results and Discussion

Figure 4 shows the distribution of scores for the three different door widths. For each width, there are 240 trials (16 participants with 15 trials each) broken into 20-mm response categories. The black and white horizontal bar at the top of the graph indicates the deviation at which the wheelchair would hit (black) or miss (white) the side of the doorway, taking into account the width of the wheelchair itself. Thus, any trials that fall under the white portion are misses, whereas trials under the black portion are hits. It is clear that the number of collisions decreased with increases in door width. The graphs also show that the data appear to be normally distributed, with relatively few outliers skewing the data.

To assess the degree of deviation to the left and right, mean deviation was calculated for the 15 trials within each block for each individual. The data were then analyzed with an ANOVA with width (620, 750, or 1,100 mm) as a within-participants factor. There was a significant effect of width [$F(2,30) = 3.44, p < .05, \eta^2 = .187$]. Figure 4 shows that the rightward deviation increased as the width of the doorway increased. Despite the fact that the rightward deviation was weaker for the narrow doorway, post hoc t tests comparing the mean deviation for each participant with zero (no deviation) indicated that the rightward deviation was significant for all three widths (see Figure 4). The rightward deviation observed in the present experiment accords with the predominance of rightward collisions observed in the first experiment, demonstrating that the results of Experiment 1 are not specific to collisions or a specific wheelchair. The data also demonstrate that the rightward deviation occurs for a range of doorway widths. The increase in the rightward deviation with wider doorways could be related to a well-known effect of line length, whereby bisection biases increase for longer lines (McCourt & Jewell, 1999). Another possibility, which cannot be ruled out entirely, is that the effect of door width reflects changes in the wheelchair's speed. To navigate the narrow doorway more accurately, it is possible that the participants drove the wheelchair more slowly. As a result, greater accuracy for the narrow doorways may have reduced the degree of rightward deviation. Unfortunately, the speed of the wheelchair was not measured in the present study, so this hypothesis is difficult to test directly. However, examination of the spread of participants' responses for each doorway width (i.e., the standard deviation) militates against this argument. If the reduction in the rightward deviation for the narrow door

Figure 4. Distribution of responses for narrow, medium, and wide doorways in Experiment 2. Each graph represents the data from 16 participants $\times$ 15 trials (240 trials). Deviations to the left and right are reflected in negative and positive values, respectively. The data are overlaid with a normal distribution. A mean was calculated for each participant, and the mean and SD across the 16 participants are shown. A t test comparing these means with zero is also shown. The black rectangles at the top of each graph indicate deviations where the wheelchair struck one side of the doorway. The white section indicates deviations where the wheelchair did not collide with the doorway.

is the result of slower and more accurate performance, there should be a systematic decrease in the standard deviation with decreases in width. To test this, the standard

deviation was calculated for each of the widths for each participant. An ANOVA with width as a repeated measure revealed no effect of width [$F(1,15) = 1.99$, n.s.; see Figure 4 for SD values].

Line bisection data were collapsed across the two line lengths and the hand used to make the bisection. The average bisection bias was -0.73 mm, which was significantly to the left of center [$t(15) = 2.40$, $p < .05$]. To investigate the relationship between line bisection performance and wheelchair navigation, a correlational analysis was carried out. Figure 5 shows that, although the correlation was in the predicted direction (i.e., leftward line bisections were associated with rightward wheelchair deviations), it was not significant [$r(16) = -.19$, n.s.]. The lack of significance may be related to the fact that only 2 of the participants showed a leftward deviation in the wheelchair. As a result, the present design may lack the statistical power to detect an inverse correlation, whereas previous research, which has used hundreds of participants (e.g., Nicholls et al., 2008), has been able to detect such an association. In addition, although it seems reasonable to expect an association between wheelchair navigation and line bisection in the *direction* of the bias, it is less clear whether an association will also occur in the *strength* of the bias between the tasks.

EXPERIMENT 3

Besides traveling with a vehicle, there are instances in which vehicles are remotely controlled in situations ranging from mining to bomb disposal. In such situations, it is important to avoid collisions and to guide the vehicle accurately. With this in mind, in the third experiment, we explored the effects of guiding the wheelchair using a remote control. The setup of the experiment was essentially the same as that described for the second experiment, ex-

cept that the participants were stationary and sat in a chair behind the wheelchair.

Using remote control to guide the wheelchair allowed us to investigate the importance of vestibular feedback on rightward deviations. Research using driving simulators has demonstrated that vestibular information plays an important role in steering accuracy and reaction time (Wierwille, Casali, & Repa, 1983). Asymmetries in vestibular feedback are also thought to be important in the manifestation of rightward deviations during walking in neglect patients and the general population (Robertson et al., 1994). Controlling the wheelchair by remote control effectively eliminated all vestibular information related to the movement of the chair. Therefore, if the rightward deviation persisted, it could not be the result of a vestibular asymmetry.

Controlling the wheelchair via remote control also changed the distance at which the judgment was made. Thus, the participants were 2.5 m away from the wheelchair as it passed through the doorway. One outcome of this is that the visual information was more distant, rendering the task more difficult. In addition, the remote control affected the space in which the task was conducted. In the previous experiments, the doorway began in extrapersonal space but moved into peripersonal space as the wheelchair approached the doorway. In the present experiment, the doorway was always 2.5 m away. As was mentioned in the introduction, important differences are thought to exist in the cognitive and neural coding of near and far space. The effect of changes in peri- and extrapersonal space on wheelchair navigation depends on whether the coding of space is updated as the participant moves toward the door. Research by Berti et al. (2002) has demonstrated that mapping of an object in extrapersonal space occurs prior to locomotion in neglect patients and that this mapping is not updated until the object is reached. Assuming that a similar process operates in the general population, a rightward deviation should continue to be observed. Alternatively, the mapping might be dynamic and change as a function of near and far space. If this is the case and a rightward deviation was not observed in this experiment, it would have repercussions for the hypothesis that the rightward deviations/bumping are the result of a rightward mis-bisection in extrapersonal space.

Method

Participants. Sixteen right-handed ($\bar{x} = +9$) undergraduate students (12 of them female, 4 male) participated in this experiment. All other characteristics were the same as those described in the first experiment.

Apparatus and Procedure. This experiment was identical in most regards to the second experiment, with one major exception. Instead of sitting in the wheelchair, the participants sat in an armchair, immediately behind the starting position of the wheelchair. Like on the wheelchair, the joystick was located over their laps, along their midlines. The wheelchair controls were connected to the wheelchair via an 8-m-long electric cable. On half of the trials, the trial began with the cable coiled to the left of the wheelchair. On the other half of the trials, the cable was coiled to the right. As with previous experiments, the joystick was operated bimanually, and the participants were asked to direct the wheelchair through the middle of the aperture, aiming for the line 2.5 m beyond the door frame. As in Ex-

Figure 5. Scatterplot showing the relationship between mean wheelchair deviation and mean line bisection deviation within participants in Experiment 2. In both cases, negative and positive scores indicate biases to the left and right, respectively.

periment 2, the participants completed three blocks of 15 trials, with doorway width (620, 750, and 1,100 mm) varied between blocks.

Results and Discussion

Figure 6 shows the distribution of scores for the three doorway widths, with 240 trials for each. As in the previous experiments, the data are normally distributed and are significantly shifted to the right. Unlike in Experiments 2 and 3, however, the distributions are much wider and the standard deviations are larger. This suggests that the participants found it more difficult to control the wheelchair by remote control. This difficulty could be related to the lack of vestibular feedback (Wierwille et al., 1983) or the distance at which the wheelchair and doorway were viewed. Unlike in Experiment 2, which also manipulated the width of the doorway, the rightward deviation did not increase for wider doorways [$F(2,30) < 1$]. The increased level of error (standard deviation) may have obscured any effect of width.

Although controlling the wheelchair via remote control was more difficult, the rightward deviation observed in the previous experiments persisted. Operating the wheelchair via remote control provided no vestibular feedback that was relevant to the motion of the chair. The rightward deviation therefore cannot be the result of a vestibular asymmetry of the type suggested by Robertson et al. (1994). The data also demonstrate that rightward deviations occur irrespective of whether the participant is sitting in the wheelchair as it passes through the doorway or is 2.0 m from the doorway. The consistency of the rightward deviation is in line with the suggestion that the trajectories are mapped at the beginning of the transit and are not remapped until the object is reached (Berti et al., 2002). Whether the rightward deviation persists for distances greater than 2.5 m remains to be determined.

EXPERIMENT 4

In all of the previous experiments, participants were asked to navigate through a doorway, and more rightward collisions or deviations were consistently observed. Two possible explanations were proposed for these rightward collisions/deviations in the introduction. The first suggested that rightward collisions/deviations were the result of a rightward mis-bisection of the space separating the two doorposts. This rightward bisection could be related to a well-known propensity for pseudoneglect to reverse from a leftward bisection bias for lines in peripersonal space to a rightward bisection bias for lines in extrapersonal space (Gamberini et al., 2008; Longo & Lourenco, 2006; Lourenco & Longo, 2009). Alternatively, rightward collisions/deviations could stem from an inability to disengage attention from the left doorpost. In this case, peripersonal and extrapersonal space might not be an important factor. In line with the reaction time studies showing a difficulty in disengaging attention from the left (Evert et al., 2003; Maril et al., 2007; Okada et al., 2006), the leftward doorpost may capture attention, making it difficult to disengage attention and shift it to the rightward doorpost. As a result of focusing attention to the left, par-

Figure 6. Distribution of responses for narrow, medium, and wide doorways in Experiment 3. Each graph represents the data from 16 participants $\times$ 15 trials (240 trials). For more details about the graph, refer to the caption for Figure 4.

ticipants concentrate on avoiding the leftward doorpost, causing rightward deviations and collisions.

This experiment tested the two explanations of rightward deviations/collisions by manipulating the salience of the doorway. In the *doorway-present* condition, a doorway was clearly defined by two towers of stackable plastic crates. As in all the previous experiments, the participants

were asked to drive themselves and the wheelchair through the middle of the two “doorposts.” It was anticipated that a rightward deviation would emerge in this condition and that this could occur in accord with either of the theories presented above. In the *doorway-absent* condition, the doorposts were removed, leaving a line drawn across the floor. In this case, the participants drove the wheelchair though the center of the line. It was expected that this condition would decrease the salience of the sides of the doorway and would, therefore, reduce the effect of asymmetries in disengagement. If the rightward deviation were to be reduced or annulled in this condition, it would suggest that the doorposts and their salience play a role in asymmetries in wheelchair navigation. Alternatively, if rightward deviations persist, it would suggest that bisections of space play a more important role.

Method

Participants. Twelve right-handed ($\bar{x} = +7$) undergraduate students (9 of them female, 3 male) participated in this experiment. All other characteristics were the same as those described in the first experiment.

Apparatus and Procedure. This experiment was identical in most regards to the second experiment, except for the following points. The doorway apparatus described in Experiment 2 was replaced with two towers of plastic, stackable crates. This was done so that the doorway could be readily assembled and dismantled within an experiment. When stacked, the towers were 1.6 m high and 400 mm square. The two towers were set so that they were separated by a horizontal distance of 750 mm. A line, which was easily visible, was drawn across the floor from the inner edge of one tower to the inner edge of the other. For half of the trials, the participants were asked to navigate themselves and the wheelchair through the middle of the two towers. On the other half of trials, the two towers were removed. In this case, the participants navigated the wheelchair through the middle of the line. The doorway-present and doorway-absent conditions were run in two separate blocks of 20 trials. The order in which the blocks were administered was balanced.

Results and Discussion

Figure 7 shows the distribution of scores for the doorway-present and -absent conditions. Each graph represents 240 trials. As in the previous experiments, the data are normally distributed and are significantly shifted to the right. There was no difference in the rightward deviation between the doorway-present and doorway-absent conditions [$t(11) < 0$], and both conditions showed a significant rightward deviation (see Figure 7). The fact that a rightward deviation was observed for the doorway-present condition, which used two towers of plastic crates, demonstrates that the deviation was not specific to the curtain arrangement used in the previous experiments. There was no sign that the rightward deviation was diminished in the doorway-absent condition. The effect was therefore not reliant on the physical presence of doorposts. By removing the doorposts, we significantly reduced the salience of the doorposts and, therefore, reduced their ability to capture attention. Although the ends of the lines in the doorway-absent condition may have captured attention to some extent, it is likely that the extent of this capture was reduced. The results therefore favor the theory that the participants were bisecting the doorway space to the right.

Figure 7. Distribution of responses for the doorway-present and doorway-absent conditions in Experiment 4. Each graph represents the data from 12 participants $\times$ 20 trials (240 trials). For more details about the graph, refer to the caption for Figure 4.

EXPERIMENT 5

So far, in all of the experiments, a wheelchair was used, which was controlled with a joystick. The advantage of this type of control is that it can be operated bimanually and requires a minimal level of movement. The disadvantage of joystick control is that it is relatively difficult for novices to operate accurately and can result in moderately large and unintentional deviations. It is therefore possible that the rightward deviation observed in the previous four experiments is peculiar to joystick control and is not the result of a more general attentional bias. This issue was addressed in this experiment by repeating Experiment 2, but using an electric scooter. The electric scooter used in this experiment is the type typically used by individuals with mobility impairments. The scooter has four wheels and is steered using a handlebar, similar to the operation of a bicycle. Given the ease with which the scooter can be operated, we expected accuracy, as reflected by a smaller standard deviation, to be much higher in the present experiment. If the rightward deviation is the result of a general attentional bias, a rightward deviation should also be observed for the electric scooter. In addition, in line with the results of Experiment 2, the rightward deviation should increase with increases in the width of the doorway.

Method

Participants. Sixteen right-handed ($\bar{x} = +8$) undergraduate students (10 of them female, 6 male) participated in this experiment. All other characteristics were the same as those described in the first experiment.

Apparatus and Procedure. This experiment was identical in most regards to the second experiment, with one major exception. Instead of a wheelchair, an electric scooter was used (model: Invacare Auriga 10). The scooter was steered by turning a set of handlebars to the left or right. A lever ran across the front of the handlebars and was pivoted at the midline. Pulling the lever toward the handlebar on the left side (and releasing it on the right) resulted in forward movement. Correspondingly, pulling the lever toward the handlebar on the right (and releasing on the left) caused the scooter to stop and/or go in reverse. Thus, like the wheelchair, the scooter required bi-manual operation. The scooter was slightly wider (605 mm) than the wheelchair (600 mm), and to accommodate this extra width, the narrowest width was increased to 635 mm. The other widths were the same. As in Experiment 2, the participants completed three blocks of 15 trials, with doorway width varied between blocks.

Results and Discussion

Figure 8 shows the distribution of scores for the three doorway widths, with 240 trials for each. It is clear that the spread of the distributions is much smaller than in the previous experiments, indicating that the electric scooter is easier to navigate than an electric wheelchair. There was a significant effect of doorway width [$F(2,30) = 15.5$, $p < .001$, $\eta^2 = .501$], whereby the rightward deviation increased for the wider doorways. Examination of the spread of the distributions, as indexed by the SD , also reveals that the amount of error increased for the wider doorways. When the means of each width were compared with zero, t tests revealed a significant rightward deviation for medium and wide doorways, but not for the narrow doorway (see Figure 8). The rightward deviation for the scooter replicates the rightward deviation observed for the electric wheelchair. The rightward deviation therefore seems to be the result of a general attentional bias, rather than a specific result of joystick control. An increase in rightward deviation for wider doorways also replicates the effect of length observed in the second experiment. It is possible that no rightward deviation was observed for the narrow doorway because of the low level of error in this condition. For wider doorways, it was more difficult to judge the middle of the passage, resulting in a higher level of error, which allowed the rightward deviation to manifest.

EXPERIMENT 6

Experiment 4 demonstrated that rightward deviations occur in the absence of doorposts and can occur for a line placed on the floor. This suggests that competition for attention between the doorposts is less important than a bisection bias for the space separating the doorposts. To examine this issue further, this experiment investigated the relationship between pointing and navigation behavior. Before navigating the doorway, the participants marked the middle of the door, using a laser pointer. Previous research in which a laser pointer was used to bisect lines has shown that the leftward bias for lines in interpersonal

Figure 8. Distribution of responses for narrow, medium, and wide doorways in Experiment 5. Each graph represents the data from 16 participants $\times$ 15 trials (240 trials). For more details about the graph, refer to the caption for Figure 4.

space (300 mm) reverses to a rightward bias for lines in extrapersonal space (1,200 mm) (Longo & Lourenco, 2006). Given that the door space was 2.5 m from the participant, a rightward bisection bias was therefore expected for the laser-pointing task. If a participant's initial perception of the midpoint of the door affects their subsequent position as they pass through the door, two predictions can be made. First, the rightward deviation for laser pointing should be equivalent in magnitude to the rightward deviation for the scooter/wheelchair. Second, there should be a positive correlation between the position indicated by the laser pointer and the subsequent deviation of the scooter/wheelchair.

Method

Participants. Sixteen right-handed ($\bar{x} = +9$) undergraduate students (11 of them female, 5 male) participated in this experiment. All other characteristics were the same as those described in the first experiment.

Apparatus and Procedure. This experiment borrowed some of the techniques developed in the previous experiments. As in Experiment 5, an electric scooter was used. The doorway was created using the stackable crates used in Experiment 4, with their inner edge separated by a horizontal distance of 1,100 mm. The participants completed 30 trials. At the beginning of each trial, a length of 50×12 mm wood was placed so that it spanned the two sides of the door. The piece of wood was 1.8 m long, ran parallel 800 mm above the ground, and was painted white. The wood provided the participants with a surface to indicate the midpoint between the two inner edges of the door. The participants marked the middle of the doorway using a laser pointer, which was mounted on a small tripod. The tripod was fixed to the center of the front handlebars of the scooter, and the participants used both hands to activate the laser and manipulate it. The participants were seated in the scooter while they made the bisection. Once the participants were satisfied that they had located the middle of the door, the piece of wood was removed. The participants were then asked to drive the scooter through the middle of the doorway. As in the previous experiments, video recordings were used to measure deviations for the pointing and navigation phases of the experiment.

Results

Figure 9 shows the point and navigation data, where each graph represents 480 trials. The distribution for the laser-pointing phase showed a significant bias of 13.2 mm to the right (see Figure 9). This rightward bias replicates the bias observed by Longo and Lourenco (2006) for laser pointing in extrapersonal space. The scooter also deviated significantly to the right, with a mean deviation of 36.4 mm. It is interesting to note that this rightward deviation was significantly larger than the deviation observed for the 1,100-mm doorway in Experiment 5 (10.5 mm). Although there is no obvious reason for this increase, it is possible that the laser-pointing task made the (misplaced) midpoint of the doorway more salient, causing a stronger rightward deviation.

If the laser-pointer biases and scooter deviations reflect the operation of the same mechanism, it would seem reasonable to expect that they would be of a similar magnitude. Contrary to this expectation, the rightward bias for laser pointing was significantly smaller than the rightward deviation for the wheelchair [$t(15) = 3.71, p < .005$]. Similarly, one might expect that the bias for laser pointing would be related to the subsequent deviation of the scooter within each trial. To test this, the data were made into a list comparing the biases for the laser-pointing and scooter phases within each trial (480 cases in all). There was no sign of a correlation between the biases [$r(480) = .025, n.s.$].

The rightward bias for laser pointing was in the correct direction and could form the basis for the rightward deviation for the scooter. That said, there does not appear to have been a strong association between the biases for the laser-pointing and scooter phases. There are a number of possible explanations for this. First, the laser-pointing and scooter phases used very different sets of perceptual and motor mechanisms. Thus, although the rightward biases

Figure 9. Distribution of responses for laser pointing and scooter navigation in Experiment 6. Each graph represents the data from 16 participants $\times$ 30 trials (480 trials). For more details about the graph, refer to the caption for Figure 4.

were derived from the same misperception of space, their ultimate value was affected by task-specific demands. Second, like the correlation in Experiment 2, there were relatively few data points that fell into the left-left quadrant of the scattergram (only 3 trials out of 480). Selection of individuals with distinct leftward biases may help to make a stronger correlation.

GENERAL DISCUSSION

This series of experiments examined whether the rightward asymmetry in collisions that has been observed for ambulatory tasks (Nicholls et al., 2007; Nicholls et al., 2008) also would occur for the operation of a wheelchair. For manual wheelchairs, no collision asymmetry was observed. However, a consistent rightward bias was observed for the electric wheelchairs irrespective of whether the bias was measured in terms of the number of hits to the right or the magnitude of the deviation. Examination of the distribution of deviations clearly illustrates that this behavior is not the result of a few outliers but reflects a general shift in the distribution toward the right. The first experiment also demonstrated that asymmetries in navigation were a relatively stable characteristic within individuals. The deviation does not appear to be the result

of an asymmetry in the control or mechanics of the wheelchair. Throughout the experiment, a number of different electric wheelchairs were used, and a consistent rightward deviation was observed. In the final two experiments, an electric scooter was used instead of a wheelchair. The scooter is maneuvered using a set of handlebars, whereas the wheelchair is guided using a joystick. The rightward deviation is therefore not specific to the mechanism used to control the vehicle.

One of the most remarkable features of this set of experiments was the persistence of the rightward deviation. Thus, despite significant changes in methodology between experiments, a rightward deviation of varying magnitudes was observed. The magnitude of the rightward deviation was often small and ranged from 10 to 36 mm for a doorway that was 1,100 mm wide. One might therefore argue that the degree of deviation is relatively insignificant. However, as was shown in the first experiment, small deviations to the right in a very narrow doorway will lead to rightward collisions. Furthermore, it is perhaps not that surprising that the degree of deviation is small. If humans had a large deviation to the right, it would be to an evolutionary disadvantage. As it stands, the rightward deviation observed in the present set of experiments may reflect imprecision in the system, but not to the point of an evolutionary weakness. Indeed, the rightward deviation might be epiphenomenal to hemispheric lateralization of function in humans, which is almost certainly beneficial in an evolutionary sense (Corballis, 1991).

It is possible that the rightward deviation for the operation of electric wheelchairs is related to a learned behavior, such as driving a car. There are two reasons to question this proposition. First, the operation of the electric wheelchair was deliberately designed to remove any asymmetrical cues, which could bias performance. Thus, the joystick was moved to the midline, and any asymmetrical cues related to the doorway or the room were removed. In this sense, the task was quite unlike driving a car, which has many asymmetries related to the driving position and road rules. Second, the vast majority of the participants were Australian drivers, who are used to driving on the left side of the road. If driving habits affected wheelchair deviation, it should bring about a leftward deviation, which is the opposite of what was observed in the present study. That said, it is difficult to know exactly what cues are used by drivers to locate their vehicle on the road. For Australian drivers, on a road divided into lanes, it is possible that they drive slightly toward the right to avoid obstacles on the left. To rule out the effect of driving habits entirely, it would be necessary to compare drivers from countries who drive on the left or right side of the road.

The rightward asymmetry in collisions observed by Nicholls et al. (2007; Nicholls et al., 2008) and the rightward deviation in the present study are also unlikely to be directly related to the mechanisms that bring about *veering*. Veering is the tendency in animals and humans to turn characteristically to one side during locomotion. In animals, the asymmetry is driven by asymmetries in dopaminergic activation, causing a turning bias away from the more active hemisphere (Pycck, 1983). In hu-

mans, turning biases are often observed by blindfolding the participant and then asking him or her to walk in a straight line. Blindfolding forces the participant to rely on idiothetic information, such as vestibular signals, afferent proprioceptive signals, and the efferent signals sent to the muscles. In such a situation, the participant will veer from the straight path. In contrast to the study by Nicholls et al. (2007; Nicholls et al., 2008) and the present study, there is little support for a consistent directionality in veering (Mohr & Lievesley, 2007). In addition, unlike the present study, when provided with allothetic information, such as optic and acoustic flows, the veering disappears.

Robertson et al. (1994) proposed that asymmetries in the vestibular system could account for the rightward deviations in neglect patients and in the general population. Experiment 3, in which participants operated the wheelchair by remote control, effectively removed any vestibular input that was related to the task. Despite this change, the rightward deviation persisted. Robertson et al. also discussed another possibility related to a more general attentional asymmetry. In this case, attention is captured by the doorpost that falls in the attended (left) hemispace, whereas the doorpost that falls in the unattended (right) hemispace is partly ignored. Pseudoneglect may provide the basis for the leftward bias in attention whereby cues presented to the left are harder to disengage attention from (Evert et al., 2003; Maril et al., 2007; Okada et al., 2006). Although this theory cannot be ruled out at this stage, it provides a less parsimonious explanation of the data. By removing the doorposts in Experiment 4, the ability of the two sides of the door to capture attention should have been decreased to some extent. Despite this decrease in salience, there was no change in the magnitude of the rightward deviation. A similar logic has been used by D'Erme, Robertson, Bartolomeo, Daniele, and Gainotti (1992). They found that removing markers placed to the left and right significantly improved neglect patients' ability to disengage attention from the right side and detect targets on the left.

An alternative explanation focuses on line bisection performance in extrapersonal space. Research consistently shows that the leftward bisection bias for lines in peripersonal space reverses to a rightward bias when the lines are placed in extrapersonal space (Longo & Lourenco, 2006). In line with this research, we demonstrated that participants made rightward bisections with a pointer prior to navigating a scooter through a doorway. It is therefore possible that participants mentally mark a position in space between the doorposts and then head toward this point. In order for this mechanism to work, navigation of the wheelchair must be ballistic, in the sense that a target position is identified in extrapersonal space and participants do not update this target as they head through the doorway (see Berti et al., 2002). The fact that the magnitude of the rightward deviation did not change as a function of operating the wheelchair in near and far space (Experiment 3) supports this proposition.

One factor that has not explicitly been explored in this study is the relative contribution of motor/intentional and perceptual/attentional factors. A classic example of the

distinction between these factors has been carried out by Bisiach, Geminiani, Berti, and Rusconi (1990). Using a pulley device, Bisiach et al. made the movements of the hands either congruent or incongruent with the movement of a stylus during a line bisection task. They found that 2 out of 15 neglect patients showed *motor neglect*, which caused them to place the transector to the left of center when hand movements were incongruent with the movement of the stylus. The dissociation is supported by research showing that premotor neglect is associated with anterior lesions, whereas perceptual neglect is associated with posterior lesions (Mesulam, 1981). Within the pseudoneglect literature, there is also some support for motor and perceptual factors. Using the lever device designed by Bisiach et al., MacLeod and Turnbull (1999) found a reduction of pseudoneglect in the incongruent condition, but only for the left hand. It should be noted, however, that pseudoneglect occurs even when the response dimension is orthogonal to the dimension of interest (Nicholls & Roberts, 2002) or when motor factors are minimized (McCourt & Jewell, 1999).

Although it is possible that motor/intentional biases played a role in the rightward deviations and collisions observed in the present study, there are a number of reasons to suspect that their influence would be minimal. First, studies investigating the effect of motor/intentional factors on pseudoneglect have used quite explicit movements toward the left or right hemispace. For instance, MacLeod and Turnbull's (1999) task required movements of 100 mm from the left or right hemispace to the midline. Similarly, Dupierrix, Alleysson, Ohlmann, and Chokron (2008) found that pointing movements of up to 182 mm to the left or right hemispace caused a shift in perceptual and motor versions of a line bisection task toward the stimulated hemispace. In the present study, movements were sometimes minimal. In the case of the electric wheelchair, movements of the joystick of just 20 mm to the left or right were sufficient to navigate the wheelchair through the doorway. It seems unlikely that small bimanual movements on a centrally located joystick would provide the basis for strong motor asymmetries. Another reason for suspecting that motor/intentional effects have a minor role in the navigation asymmetries is the effect of door width on the rightward deviation (Experiments 2 and 5). The amount and type of movement required to guide the electric wheelchair and scooter through a narrow or wide doorway would have been similar. If the rightward deviations were the result of motor/intentional factors, the rightward deviation should have been constant. Instead of this, the rightward bias increased for wider doors, consistent with the perceptual/attentional explanation.

The present set of experiments has demonstrated a persistent deviation to the right when an electric wheelchair or scooter is navigated through a doorway. Rightward biases for bisecting lines in extrapersonal space provide a good explanation of this deviation. Although the wheelchairs and scooters used in this study provide a good analogy for navigational behaviors that occur in an everyday setting, the generality remains to be tested. It would be interesting to see whether a similar rightward deviation would occur

when one navigates a more complicated or longer course, a larger vehicle such as a forklift, or a course in virtual reality. It would also be important to demonstrate that the rightward deviation can be corrected by the type of attentional cues that are known to be effective in ameliorating the symptoms of clinical neglect.

AUTHOR NOTE

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NOTE

1. Veering biases are the characteristic turning patterns observed in animals and humans as they walk when they are blindfolded. These biases are considered in more detail in the General Discussion section.

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