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RESEARCH ARTICLE

Directional bias in the body while walking through a doorway: its association with attentional and motor factors

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Abstract Recent studies indicate that cognitively intact individuals experience frequent rightward collisions while walking through narrow doorways. Such a directional bias has been attributed to an attentional bias in spatial perception. However, these studies did not investigate the involvement of any motor factor that could affect the directional bias in the body. In the present study, three experiments were conducted to quantify the impact of the leading foot when crossing a doorway threshold on the directional bias in the body midpoint when passing through the doorway. Participants walked through the perceived center of a relatively wide doorway. Measurements of the deviation of the upper-body midpoint from the center of the doorway demonstrated that the leading foot had a very strong influence on the directional bias. Some participants showed rightward deviation irrespective of which foot was used to step through the doorway (Experiment 1). However, a consistent rightward bias in the body was not observed in other experiments. Both the movement of one hand (Experiment 2) and covert visual attention to one side of the door (Experiment 3) caused contralateral deviation of the body. It is likely that the movement of the hand and a visual stimulus serve as an attentional cue and are effective to avoid neglect of the ipsilateral side; as a result, the body midpoint is deviated to the contralateral side. From these findings, we conclude that the directional bias in locomotor trajectories while passing through a doorway results from the combination of a motor factor, particularly the leading foot, and attentional/brain factors.

Keywords Spatial cognition · Pseudoneglect · Attention · Obstacle avoidance · Walking

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Introduction

Recent studies demonstrate that individuals collide on the right more often than on the left when they walk through very narrow doorways (Nicholls et al. 2007, 2008). Nichcolls and colleagues asked participants to walk through a doorway that was marginally wider than each participant's body. The count of collisions on the left and the right showed a significantly larger number of rightward than leftward collisions. Nicholls et al. (2007, but not Nicholls et al. 2008) also demonstrated that hand movement while walking affected the bias in collision; movement of the right hand while walking resulted in more collisions on the left side of the doorway, whereas movement of the left hand resulted in more collisions on the right side of the doorway.

Nicholls et al. (2007, 2008) attributed rightward collisions while walking to "pseudoneglect" (Bowers and Heilman 1980). Pseudoneglect is a subtle but consistent neglect of the right hemispace that is observed when cognitively intact individuals perform visuospatial tasks, such as a line bisection (Jewell and McCourt 2000). A possible explanation for the subtle neglect of the right hemispace has been provided by an orientational bias model of unilateral neglect in brain-damaged patients (Kinsbourne 1987, 1993). According to this model, unilateral neglect in brain-damaged patients results from imbalance between the

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activities of the left and right hemispheres. The movement of the hand on the affected side activates the contralateral hemisphere and thus ameliorates the imbalance between the activities of the left and right hemispheres. As a result, the symptoms of spatial neglect can be modified through the activation of the affected hand (Frassinetti et al. 2001). Following these explanations, Nicholls et al. have suggested that the movement of the left hand caused a stronger tendency to pseudoneglect, leading to more collisions on the right side. In contrast, the movement of the right hand counteracted the pre-existing right hemisphere activity, leading to leftward inattention and more leftward bumps.

The phenomenon of pseudoneglect (i.e., a *leftward* bias in spatial perception) and collisions on the *right* side seems contradictory; if an individual intends to walk through the perceived center of a doorway and his/her estimate of the center is biased toward the left due to the subtle neglect of the right side of the doorway, then collisions should occur more often on the left side than on the right side. In Nicholls et al. (2007, 2008), given that the doorway was very narrow and that the leftward deviation of the walking trajectories was very subtle, the probability of rightward collisions due to a subtle neglect of the right door may have been much higher than the probability of leftward collision due to the leftward deviation in the walking trajectories. When a doorway is wide enough to avoid collision, however, it would be hypothesized that the neglect of the right side of the door should lead to a leftward bias in the body when crossing the threshold of a doorway.

With this contradictory issue in mind, Nicholls and his colleagues have recently proposed an alternative model which predicted a rightward mis-bisection of the aperture irrespective of the aperture width (Nicholls et al. 2010). This new model was based on the dissociation of the direction in the attentional bias between near (i.e., reachable) space and far space. Whereas cognitively intact individuals show a leftward attentional bias when they bisect a line in near space, they show an opposite, rightward bias when they bisect a line in far space (Longo and Lourenco 2006; Gamberini et al. 2008; Lourenco and Longo 2009). For the locomotor tasks used in the studies by Nicholls et al. (2007, 2008), the doorway was located in far space, i.e., 2.5 m from the location at which walking was initiated. Nicholls et al. (2010) proposed that rightward collisions would occur because the perceived center of the doorway deviates to the right in far space and an individual intends to walk through the perceived center (see Berti et al. 2002; Grossi et al. 2001 for similar discussion of brain-damaged patients).

Nicholls et al. (2010) tested their proposal with six well-designed experiments. They demonstrated that consistent rightward biases in locomotor trajectories were observed when cognitively intact participants were asked to maneuver an electric wheelchair or a scooter. Importantly, a consistent rightward bias was observed irrespective of the aperture width. Moreover, rightward deviation was observed even when the doorway was removed (i.e., only a line was drawn across the floor). These two findings were apparently inconsistent with the model based on pseudoneglect (Nicholls et al. 2007, 2008), which proposed that the subtle neglect of the right door would cause rightward collision. With these findings, Nicholls et al. (2010) concluded that rightward mis-bisection in far space is likely to provide a better explanation of the rightward collisions and deviations.

Although most of the data reported in Nicholls et al. (2010) suggested that the involvement of rightward mis-bisection of the doorway in far space could lead to rightward collisions, some data that were contrary to this model indicated that task-specific factors for locomotion could also affect the directional bias of locomotor trajectories. First, no rightward deviations of locomotor trajectories were observed when participants operated a manual wheelchair; asymmetries in strength between the hands could account for the lack of rightward deviations. Second, the magnitude of rightward deviation for locomotion by a scooter was significantly greater than that for bisection of the doorway in far space by using a laser pointer; no correlation between the rightward deviations in the two tasks was found. These findings suggest that even though the rightward biases observed in both tasks were derived from the same mechanism, the magnitude of deviations could be modified by task-specific factors for locomotion, particularly motor factors. It is, therefore, necessary to quantify the impact of relevant motor factors on the directional bias of locomotor trajectories for the discussion of the involvement of attentional/brain functions.

The primary purpose of the present study was to quantify the impact of the leading foot used in stepping through the doorway on the directional bias. The reason for investigating this issue was that Nicholls et al. (2007, 2008) did not exclude the possibility that rightward collisions resulted simply from stepping through the doorway with the right foot. When stepping with the right foot, the individual's center of mass shifts above the right foot (Patla and Vickers 2003; Shumway-Cook and Woollacott 2001); as a result, a collision is more likely to occur on the right than on the left. Unfortunately, Nicholls et al. (2007, 2008) did not record the leading foot to enter a doorway. Given that right-handed individuals prefer to step off with the right foot to initiate their locomotion, the number of steps taken at a 2.5 m distance to the doorway might have led to the right foot being used to step through the doorway. To exclude this possibility, the present study investigated whether, independently of the choice of the leading foot to step through the doorway, robust rightward deviations of the walking trajectories were observed.

The other purpose of the present study was to determine the involvement of attentional factors on the directional bias in locomotor trajectories. For this purpose, we examined the impact of the aperture width (Experiment 1), hand movement (Experiment 2), and visual attention to one side of the door (Experiment 3). We further examined whether a significant correlation existed between the directional bias observed in the walking task and that in the line bisection task performed in near space (Experiment 1) and far space (Experiments 2 & 3). With these findings, we discussed the involvement of attentional factors (i.e., the subtle neglect of one side of the door and/or the mis-bisection of the aperture in far space) and motor factors on the directional bias in the body when entering a doorway.

Experiment 1

The purposes of the first experiment were (a) to investigate the effect of the leading foot and the size of the doorway on the magnitude of deviation in the walking trajectories when stepping through a doorway and (b) to determine whether a significant correlation existed between the directional bias observed in the walking task and that observed in the line bisection task. Walking trajectories were represented by the displacement of the midpoint of the upper body.

Rather than measuring the frequency of collisions with a very narrow doorway in the previous studies (Nicholls et al. 2007, 2008), we measured the magnitude of the deviation of the upper-body midpoint from the center of a doorway with a relatively wide doorway (i.e., one where collision was unlikely to occur). We tested two doorways: one was 1.3 times the participant's body width and the other, 2.0 times. A previous study indicated that when a doorway was less than 1.3 times an individual's shoulder width, it would be perceived as narrow relative to the participant's body, and the individual would rotate his/her shoulders before entering it (Warren and Whang 1987). The model based on pseudoneglect predicted a rightward deviation of the walking trajectories to the right when the door size was 1.3 times the shoulder width and a leftward deviation when the doorway was 2.0 times the shoulder width. The model based on the directional bias in far space predicted a consistent rightward bias for both doorways.

Method

Participants

Sixteen young adults participated (eight women and eight men, age: 22.6 ± 5.4 years, shoulder width: 432 ± 43 mm). The Edinburgh Handedness Inventory (Oldfield 1971), used as a handedness questionnaire, ensured that all participants were right-handed. The experiment protocol was approved by the institutional ethics committee of the Tokyo Metropolitan University. All participants gave informed consent prior to the study.

Apparatus

This experiment was conducted in a 6.7 m × 4.9 m room at the Tokyo Metropolitan University. For the walking task, a doorway was created using two black curtains (1.2 m wide × 2 m long) suspended from a horizontal bar located 2.0 m from the ground. The doorway was located 2.0 m from the back wall. The back wall was covered with a large black curtain to prevent the participants from judging the center of the doorway based on the texture of the back wall. The body kinematics was measured with a three-dimensional motion analysis system (OQUS300SYS, Qualisys, Sweden) at a sampling frequency of 120 Hz. The motion analysis system included five cameras and tracked seven passive retroreflective markers: three markers attached to the upper back (one each on the left and right acromions; one on the point at which a line connecting the right and left scapulas crossed the spinous process), one each on the left and right calcis, and two markers attached on the inner edge of the left and right curtains to measure the width of the doorway. Walking trajectories were expressed by the displacement of the midpoint of the upper body. The upper-body midpoint was represented as the midpoint of the three markers attached on the upper body. A metronome was used to control the locomotion speed. Each participant held a 300-mm horizontal bar with both hands during the walking task (Fig. 1).

For the line bisection task, the stimulus consisted of eight horizontal lines, each of which was 100 mm long and 2 mm thick. The lines were drawn in black ink on white A4

Fig. 1 Experimental setup in all experiments. The location at which walking was initiated was adjusted so that the participants crossed the doorway on their fourth step (about 2 m). Participants initiated walking while attempting to step in time to the remembered metronome beats (84 beats/min) and tried to walk through a doorway so that the body midpoint crossed the center of the doorway

paper. The lines, printed four to a page, were spaced evenly along the vertical axis of the page but were offset slightly to either the left or right side. The stimulus was identical to that used in Nicholls et al. (2008), who found a tendency to pseudoneglect.

Tasks, protocols, and data analysis

Walking task The walking task was to approach and cross the center of a doorway (i.e., to bisect the doorway with the upper-body midpoint) as accurately as possible while holding a 300-mm horizontal bar in both hands. The participants maintained their arm posture so that their forearms were aligned horizontal to the floor and their elbows touched the edges of the front side of the body. The participants were not allowed to move their hands as they walked. The location at which walking was initiated was adjusted so that the participants crossed the doorway on their fourth step (about 2 m). The leading foot that crossed the doorway first was manipulated by asking the participants to initiate walking with their left or right foot. The width of the doorway was adjusted to 1.3 or 2.0 times the width of a participant's shoulders.

The experiment was designed so that the locomotion speed, which could affect a walking trajectory, was maintained at the determined level for all participants. For this purpose, the participants listened to metronome beats (84 beats/min) for five seconds before starting to walk. Immediately after the sound stopped, the participants initiated walking while attempting to step in time to the memorized metronome beats. This manipulation enabled the participants to maintain their locomotion speed within 100 ± 20 cm/s at the time of crossing the doorway. The metronome sound was stopped during the walking to help the participants concentrate on passing through the center of the doorway.

Prior to performing the main trials of the walking task, the participants walked through the doorway freely to determine the location at which they had to start walking in order to cross the doorway on their fourth step. They then performed four practice trials to familiarize themselves with the task (two trials initiating walking with the left foot and two trials with the right foot). The sound of metronome was presented throughout the practice trials.

The participants performed a total of twenty trials (five trials each for leading foot × two doorway widths) as the main trials. For each trial, the magnitude of the deviation in the upper-body midpoint from the center of the doorway at crossing was used as a dependent measure. A positive value of the dependent measure meant a rightward deviation. A two-way (leading foot × door width) ANOVA with repeated measures on both factors was used as a statistical test for the variable. A one-sample *t* test was conducted for the magnitude of deviation in each experimental condition to investigate whether the upper-body midpoint in each condition deviated significantly from the center of the doorway. We also calculated the absolute value of the deviation to determine whether the participants' errors in attempting to pass through the center of the doorway were affected by leading foot or door width. A two-way (leading foot × door width) ANOVA with repeated measures on both factors was used as a statistical test.

Line bisection task The protocol of the line bisection task was identical to that of Nicholls et al. (2008). The line bisection task involved using a pen to bisect horizontal lines as accurately as possible. The participants used their right hand to bisect the stimuli on one page and the left hand to do the same on the other page, with the order being counterbalanced among the participants. The magnitude of the deviation of the bisected point from the true center was measured as a dependent measure. A positive value of the dependent measure meant a rightward deviation. A one-sample *t* test was conducted to investigate whether there was any indication of pseudoneglect (i.e., leftward deviation).

We also calculated the correlation between the magnitude of the deviation of the upper-body midpoint obtained from the walking task and the magnitude of the deviation of the perceived midline obtained from the bisection task.

Results

For the walking task, the mean magnitude of the deviation from the center of an aperture when crossing the doorway is shown in Fig. 2a. Scatter plots of individual results are also shown in Fig. 2b. The two-way ANOVA showed that the leading foot significantly affected the deviation ($F(1,15) = 5.49$, $p < .05$); the upper-body midpoint deviated more to the right when crossing with the right than the left foot. Neither the main effect of the door width nor the interaction between the leading foot and door width was significant ($F(1, 15) = 0.03$, ns, and $F(1, 15) = 1.20$, ns, respectively). Figure 2a appears to show consistent rightward biases, irrespective of whether the leading foot was the left or the right one. However, the one-sample *t* test showed significant rightward deviations only when the leading foot was the right one ($t(15) = 3.89$ ($p < .01$) and 2.27($p < .01$) for the doorways of 1.3 and 2.0 times, respectively); the rightward deviation did not reach significance for the left leading foot ($t(15) = 0.54$ and 0.68, respectively).

The mean magnitude of the absolute deviation from the center of the aperture is shown in Fig. 3. The significant main effect of aperture width ($F(1,15) = 5.49$, $p < .05$) indicated that the participants had more difficulty crossing the

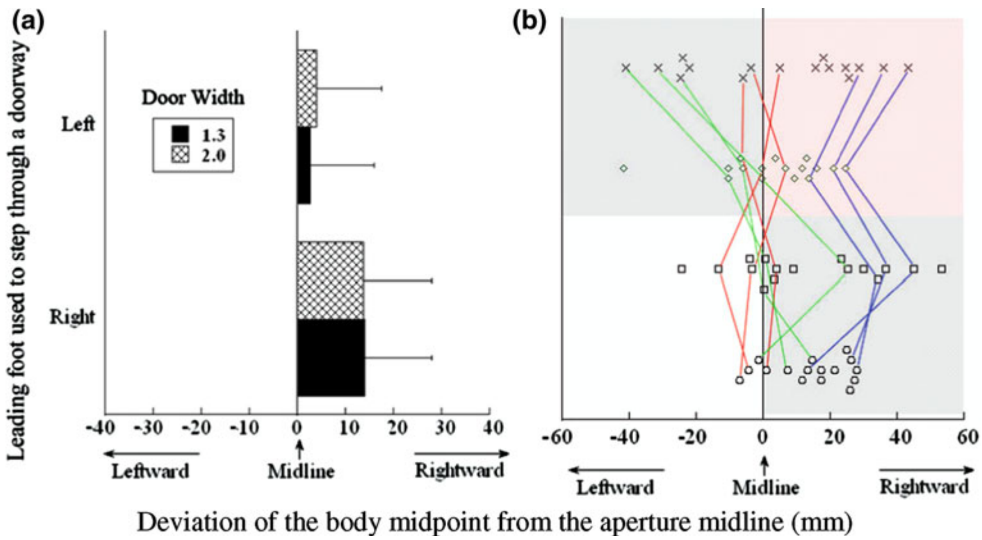

Fig. 2 **a** Mean deviation of the body midpoint from the center when crossing a doorway for each stepping foot and doorway size (SD *bars* are shown). **b** Scatter plot illustrating individual results. The plots in the *gray* areas indicate the deviation of the body midpoint in response to the side of the stepping foot, whereas the plots in the *pink* area indicate rightward deviation in spite of stepping with the left foot. The *vertical lines* show the results of selected participants who showed a deviation to the left (*green*) or right (*blue*) or no deviation (*red*) when crossing a wider doorway with the left foot. These *lines* indicate that some participants showed rightward deviations for all conditions and others showed none in any condition. The participants indicated with the *green lines* were affected by the stepping foot, i.e., showing leftward deviation for the left stepping-foot condition and rightward deviation for the right stepping-foot condition

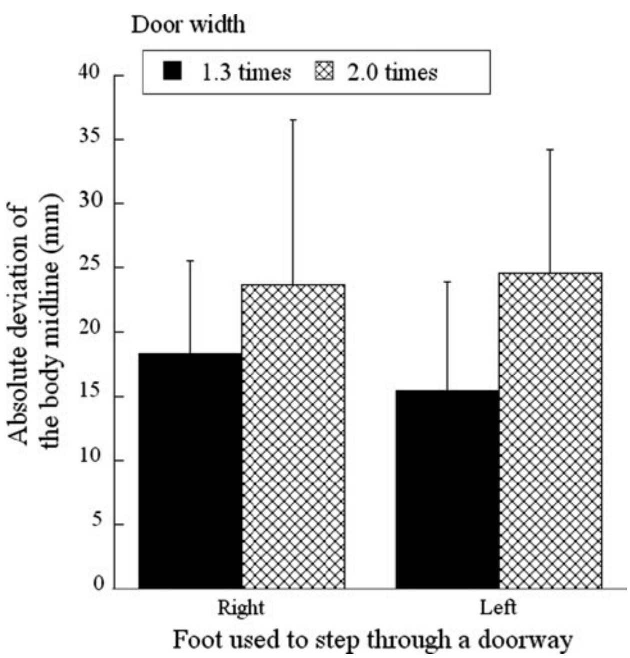

Fig. 3 Mean absolute deviation of the body midpoint from the center when crossing a doorway for each stepping foot and hand movement (SD *bars* are shown)

center of an aperture with the wider aperture. Neither the main effect of the leading foot nor the interaction between the leading foot and the aperture width was significant ($F(1, 15) = 0.16$, ns, and $F(1, 15) = 1.67$, ns, respectively).

For the line bisection task, virtually no deviation from the center was observed (overall; −0.03 mm). The one-sample *t* test showed no indication of pseudoneglect ($t(15) = 1.44$, ns). The mean absolute value of the deviation was 1.17 ± 0.8 mm, showing that the deviation itself was very small. There was no correlation between the magnitudes of the deviations obtained from the walking and line bisection tasks ($r = 0.45$, ns).

Discussion

The results indicate that the leading foot significantly affected the deviation of the upper-body midpoint when the participant crossed the threshold of the doorway. For example, the upper-body midpoint of the participant deviated more to the right when using the right foot than when using the left foot to cross the threshold. Figure 4 shows representative walking trajectories when approaching and crossing a doorway in the case of crossing with the left leading foot. These trajectories clearly show that the trajectory shifts above the leading foot at each step (the timing of each step is indicated by a footprint in the figure). This strongly suggests that measuring the impact of the leading foot is indispensable to discuss whether the directional bias in walking trajectories is attributed to attentional and brain factors.

Although Fig. 2a appears to show a consistent rightward bias, the one-sample *t* test showed significant rightward deviations of the upper-body midpoint only when the

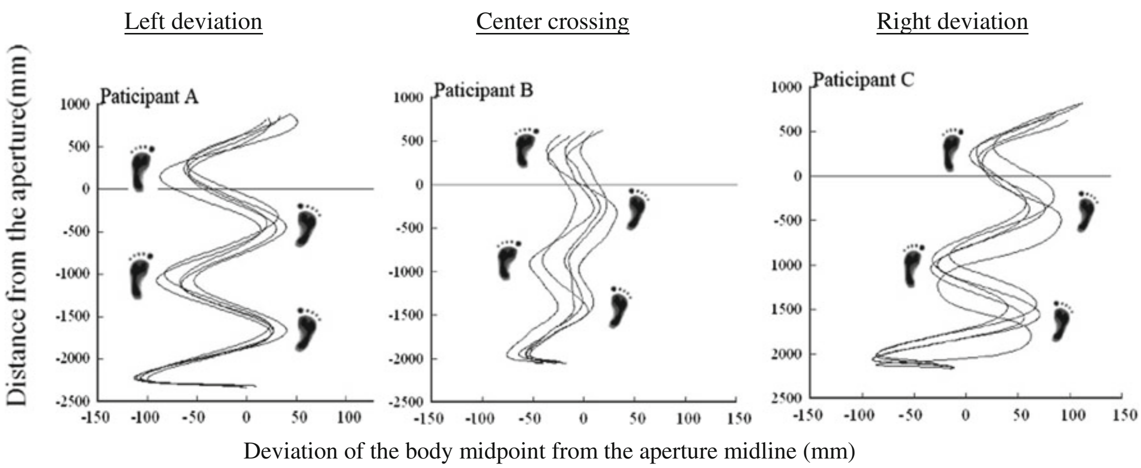

Fig. 4 Examples of walking trajectories when approaching and crossing a doorway in the case of crossing a wider doorway with the left foot. Each example was selected from the participant showing deviation to the left or right sides or no deviation in this condition (see Fig. 2b). Footprints indicate the location of the foot for each step. The body midpoint shifts over the stance limb prior to taking the first step and can deviate approximately 50 mm to the right or left depending on which foot is used (Participant A)

leading foot was the right one. However, the scatter plots of individual results (Fig. 2b) indicate that several participants showed consistent rightward deviations of the upper-body midpoint irrespectively of the leading foot. The colored vertical lines in Fig. 2b show the results of selected participants who showed a deviation to the leftward (green), rightward (blue), or no (red) deviation when crossing a wider doorway with the left foot. The green lines indicate that some participants consistently showed rightward deviations for all conditions. These findings partly support the consistent rightward bias in locomotor trajectories (Nicholls et al. 2010).

The results showed no effect of the doorway width on the directional bias. This was inconsistent with the model based on the involvement of pseudoneglect, which predicts a more leftward bias as the doorway becomes wider. Instead, the doorway width significantly affected the absolute value of the deviation, suggesting that the participants had more difficulty passing through the center of a wide doorway. This outcome is reasonable considering that the door frame would become out of focus as an individual approaches it and thus identifying the precise center would be difficult.

We found no significant correlation between the directional bias observed in the walking task and that in the line bisection task performed in near space. The critical issue with regard to this result is that in the present study, there was no tendency of pseudoneglect in the line bisection task. However, our line bisection task was identical to that used in Nicholls et al. (2008), who showed a significant tendency of pseudoneglect. The reasons for the failure to show pseudoneglect are unclear. Given that the absolute value of the deviation was very small (1.17 ± 0.8 mm), the task may have made it easy for the participants to precisely identify the center of the line.

Experiment 2

The first objective of Experiment 2 was to identify whether the effect of the hand movement on the directional bias in walking trajectories, reported in Nicholls et al. (2007), was independent of the effect of the leading foot. The model based on the involvement of pseudoneglect predicted that movement of the one hand would activate the contralateral side of the hemisphere and modify the imbalance between the activities of the left and right hemispheres. As a result, movement of the one hand should cause the deviation of the body midpoint to the *ipsilateral* side of the movement.

Importantly, Nicholls et al. (2007) reported that the right-hand movement resulted in more leftward collisions, whereas the left-hand movement resulted in more rightward collisions. These findings appeared to suggest that contrary to the predictions based on the involvement of pseudoneglect, the movement of one hand should cause the deviation of the body midpoint to the *contralateral* side of the movement. We, therefore, investigated whether the hand movement caused the deviation to the ipsilateral or the contralateral side.

The second objective was to test whether a significant correlation existed between the directional bias observed in the walking task and that in a novel, spatial bisection task, wherein a doorway-like stimulus was projected onto a large screen, located 2 m from participants, i.e., far space. The model based on the involvement of rightward mis-bisection of the doorway in far space (Nicholls et al. 2010) predicted a positive correlation between the directional bias observed in the two tasks.

Method

Participants

Twenty-four young adults (twelve women and twelve men, age: 23.3 ± 5.4 years, shoulder width: 423 ± 49 mm) participated. The Edinburgh Handedness Inventory (Oldfield 1971) was used to ensure that all of the participants were right-handed.

Tasks, protocols, and data analysis

Walking task The apparatus and protocols of the walking task were generally the same as those in the first experiment, except that (a) the participants moved their left, right, or both hands as they walked and (b) the width of the doorway was constant, 2.0 times the width of the participant's shoulders. There were three conditions with regard to hand movement: moving the left hand, moving the right hand, and moving both hands. In each condition, the participants repeatedly opened and grasped their hands in accordance with a remembered metronome beat (84 beats/min). This meant that the movement of the hand and the stepping movement were synchronized. When moving both hands, the participants simultaneously held the bar with their thumbs. The participants performed a total of thirty-six trials (six trials for each leading foot × three hand movements).

A two-way (leading foot × hand movement) ANOVA with repeated measures on both factors was performed as a statistical test. A dependent measure was the magnitude of the deviation of the upper-body midpoint from the center of the doorway when a participant was walking through the doorway. A one-sample *t* test was also conducted for the magnitude of deviation in each experimental condition to investigate whether the upper-body midpoint in each condition deviated significantly from the center of the doorway.

Spatial bisection task A doorway-like stimulus was projected onto a large screen (3.8 m wide × 2 m high) located 2 m in front of a participant in a darkroom. The stimulus was an aperture composed of two black rectangles (500 mm wide × 700 mm high), similar to that used in the walking task. The standard width of the aperture was adjusted to 2.0 times the width of the participant's shoulders. The width of the aperture presented to each participant was randomly chosen from 90, 100, and 110% of the standard width. The position of the center of the aperture was randomly located at one of three conditions (0, 50 mm left, or 50 mm right from the center of the screen).

The participants were requested to accurately bisect a presented aperture with an arrow projected on a screen by manipulating a computer mouse with the right hand. They clicked the right button of the mouse when they determined the perceived midpoint. The next trial started immediately after the participant bisected the aperture. Each participant performed a total of fifty trials. Bisection performance was measured in mm to the left or right of the true center. Positive values reflected errors to the right. A one-sample *t* test was used as a statistical test to determine whether the bisection errors were significantly to the left or right of zero. We calculated the correlation between the magnitude of the deviation of the perceived midpoint in the spatial bisection task and the magnitude of the deviation of the upper-body midpoint obtained from the both-hand moving condition in the walking task.

Results

Walking task

Figure 5a shows the mean magnitudes of the deviation of the upper-body midpoint from the center of the aperture when crossing the doorway in Experiment 2. The two-way ANOVA showed a significant main effect of the leading foot ($F(1, 23) = 50.79$, $p < .01$); the upper-body midpoint deviated more to the right with right-foot crossing than it did with left-foot crossing. The main effect of hand movement was also significant ($F(2, 46) = 14.65$, $p < .01$). Multiple comparisons indicated that the upper-body midpoint deviated more to the right with left-hand movement than with right-hand and both-hand movements. No significant interaction between leading foot and hand movement was found ($F(2, 46) = 1.2$, ns). The one-sample *t* test showed that for the right leading foot, significant rightward biases were observed in the right-hand ($t(23) = 4.17$, $p < 01$) and both-hand conditions ($t(23) = 2.19$, $p < 05$), whereas for the left leading foot, significant leftward biases were observed in the both-hand ($t(23) = 2.59$, $p < 05$) and left-hand conditions ($t(23) = 3.21$, $p < 01$).

Spatial bisection task and correlation between the performances of the two tasks

The average value of the bisection performance bias was −28.3 mm. The one-sample *t* test showed that contrary to the prediction of rightward deviation for the bisection task performed for stimuli in far space, the bisected point was significantly deviated toward the left side ($t(24) = 6.63$ $p < 0.05$). Figure 5b shows the relation between the results of the walking task and of the spatial bisection task in each experiment. There was no significant correlation ($r = 0.13$, ns).

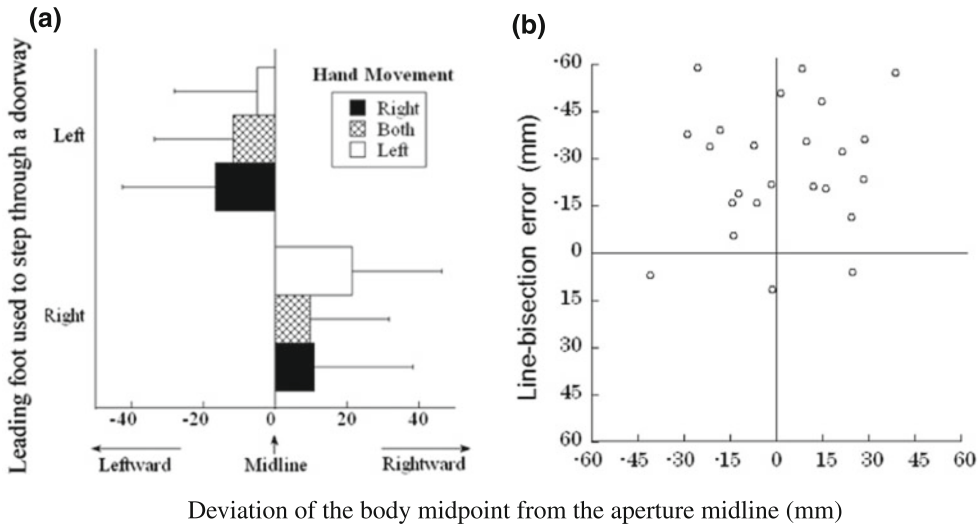

Fig. 5 **a** Mean deviation of the body midpoint from the center when crossing a doorway for each stepping foot and hand movement in Experiment 2 (SD *bars* are shown). **b** Scatter plot illustrating the lack of relationship between the spatial bisection task and the walking task

Discussion

The present experiment replicated the results of Experiment 1 in that the leading foot significantly affected the deviation of the upper-body midpoint. Independently of such strong effect of the leading foot, the left-hand movement caused deviation of the upper-body midpoint to the contralateral side, although the right-hand movement did not significantly affect the deviation. This partly suggests that the movement of one hand caused the deviation of the body midpoint to the contralateral side of the movement. This was apparently contrary to the predictions based on the involvement of pseudoneglect (i.e., the deviation to the ipsilateral side of the movement).

One of the plausible explanations for the finding was that the hand movement may have functioned as an attentional cue that effectively prevented the neglect of the ipsilateral side (attentional cueing hypothesis). This explanation was what Nicholls et al. (2007) has mentioned as one of other possible explanations for the hand-movement effect. If this explanation was the case, then not only the hand movement but any perceptual stimuli which function as attentional cues should cause the deviation of the body midpoint to the contralateral side. We tested this hypothesis in Experiment 3 with a visual attentional cue.

The results of the spatial bisection task showed a significant leftward bias of the bisected point. This was a typical tendency of pseudoneglect in near space and was contrary to the previous findings demonstrating a rightward deviation for the bisection task performed for stimuli in far space (Longo and Lourenco 2006; Gamberini et al. 2008; Lourenco and Longo 2009; Nicholls et al. 2010).

The reason for the discrepancy between the present and previous findings may have resulted from the differences in the way that participants indicated their perceived midpoint. The participants in the present study clicked the right button of the mouse, whereas those in the previous study used a laser pointer. It appears that the use of a computer mouse brings the doorway stimulus into near space. Such phenomena have been reported in the study of tool use. When a laser pointer was used, individuals showed a consistent rightward bias in bisection for a line stimulus located in far space. When a long stick was used, however, a leftward bias was observed for the same stimulus, similar to that observed with a laser pointer in near space (Longo and Lourenco 2006). Such effect of tool use was observed even in a virtual environment; that is, the use of a virtual stick caused a leftward bias in bisection for a line stimulus located in virtual far space (Gamberini et al. 2008). Similar to such phenomena, the manipulation of an arrow projected on a screen by the computer mouse in the present study may have led to the representation of the doorway stimulus as the stimulus in near space.

Finally, there were no significant correlations between the performance on the spatial bisection task and the walking task. This replicated the results of Experiment 1. The suggestions of this finding are discussed in the "General discussion".

Experiment 3

Experiment 3 investigated the effect of visual attentional cueing to test whether the modulation of the directional bias in the upper-body midpoint accompanied by the hand movement in Experiment 2 could be explained as the result of an attentional cue that effectively prevented the neglect of the ipsilateral side. The experiment was designed so that participants covertly attended to the frame of the door while their gaze was maintained on the perceived center of the doorway.

Method

Participants

Twenty young adults participated (eleven women and nine men, age: 23.1 ± 5.9 years, shoulder width: 460 ± 40 mm). A handedness questionnaire (the Edinburgh Handedness Inventory; Oldfield 1971) was used to ensure that all participants were right-handed.

Apparatus

The experimental setup of the walking task was generally the same as that used in the first experiment. To manipulate the direction of participants' covert visual attention, a custom-made device for illuminating a light-emitting diode (LED) was used (Uchida Electric, Inc., Japan). This device consisted of two LEDs (10 mm in diameter) that emit red, blue, or green light. An optoelectric timing gate triggered illumination by the LEDs, and a computer controlled the timing, location, and color sequences of the LED illumination. The LEDs were attached to the inner side of the door frame to match the participant's eye height. The optoelectric timing gate was 300 mm from the ground, i.e., at around knee level, and was located at the start position of the walking task.

To check that the participant's gaze was directed toward the perceived center of the doorway even when the LED illuminated the door frame, the direction of gaze was measured with an Eye Mark Recorder (EMR-9, Nac Inc., Japan) at a sampling frequency of 30 Hz. To measure the angle of yaw head rotation (i.e., motion around the longitudinal axis) at the time of passing through the doorway, a triad of reflective markers was attached to the head. The locations of these markers were tracked with OQUS cameras. The measurement of the head rotation was necessary to determine whether a participant rotated his head toward a location illuminated by the LED so as to improve his/her peripheral vision.

Tasks, protocols, and data analysis

The protocols of the walking task were generally the same as those in the first experiment except that the participants needed to covertly attend to the illuminated LED. There were four conditions for LED illumination: (1) flashing on the left side of the door frame, (2) flashing on the right side of the door frame, (3) flashing on both sides, and (4) absence of illumination. For each condition, the LED illuminated a sequence of red, blue, and green in a random order as soon as the participants started walking. Each illumination lasted for 300 ms at an interval of 100 ms. The setting enabled the participants to covertly attend to all three types of LED illumination as they took the first two steps. Because the doorway was relatively wide (i.e., 2.0 times the body width), this time setting was necessary for the participants to covertly attend to the LED illumination without eye or head rotation. To determine whether the participants successfully attended to the sequence of the LED illumination, they were asked to report the order of illumination after they stopped walking. If their report was correct, then the participants performed the next trial; otherwise, they repeated the same trial until they reported a correct answer.

The participants performed a total of 40 trials (five trials for each leading foot × four LED illuminations). The order of the leading foot and LED illumination was counterbalanced among the participants. Trials in which a participant shifted his/her gaze toward the LED were excluded from the analysis. A two-way (leading foot × LED illumination) ANOVA with repeated measures on both factors was used for analyzing each of the directional bias in the upper-body midpoint and of the head rotation angle. A one-sample *t* test was also conducted for the magnitude of deviation in each experimental condition to investigate whether the upper-body midpoint in each condition deviated significantly from the center of the doorway.

Results and discussion

The preliminary analysis of the gaze behavior ensured that there was no trial in which the participants shifted their gaze toward the LED while walking; therefore, no trial was excluded from the analysis due to covert attention to the LED illumination. Furthermore, the measurements of yaw head rotations showed virtually no head rotation when crossing the doorway (average = 2.12 ± 1.24 degrees, all trials <7 degrees). The two-way ANOVA showed no significant effect of the leading foot ($F(1, 19) = 0.21$, ns) or of LED illumination ($F(3, 57) = 0.55$, ns) and no significant interactions.

The mean magnitudes of the deviation of the upper-body midpoint from the center of the aperture when crossing the doorway are shown in Fig. 6. The two-way ANOVA showed significant main effects of the leading foot ($F(1, 19) = 53.68$, $p < .01$) and LED illumination ($F(3, 57) = 3.56$, $p < .05$). Multiple comparisons indicated that the upper-body midpoint deviated more to the right on the

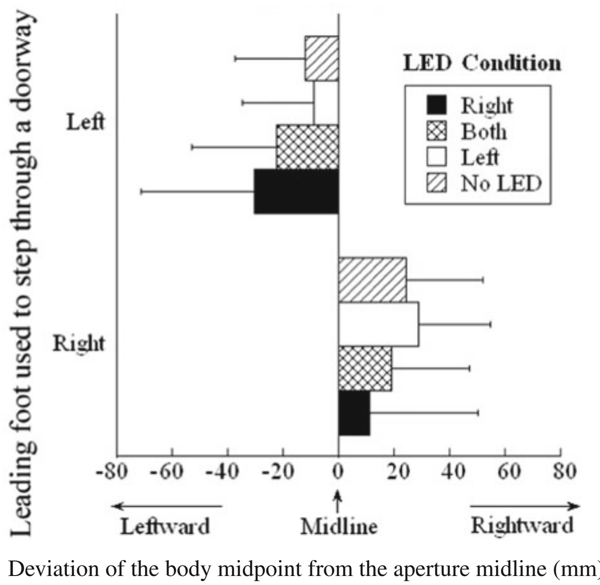

Fig. 6 Mean deviation of the body midpoint from the center when crossing a doorway for each stepping foot and LED illumination in Experiment 4 (SD *bars* are shown)

left illumination condition than the right illumination condition. There was no significant interaction between the leading foot and LED condition ($F(3, 57) = 0.21$, ns). The one-sample *t* test showed that for the right leading foot, significant rightward biases were observed in all but the right LED conditions, whereas for the left leading foot, significant leftward biases were observed in all but the left LED conditions.

The results showed that independently of the leading foot to step through a doorway, covert visual attention to one side of the door edge shifted the upper-body midpoint to the contralateral side. Therefore, movement of one hand and covert visual attention to one side of the door had similar effects on the directional deviation of the upper-body midpoint. This supported the attentional cueing hypothesis. It is important to note that previous studies demonstrating pseudoneglect in a line bisection task have reported that the bisected point deviated toward the ipsilateral side of visual cueing (Milner et al. 1992; Nichelli et al. 1989). The present findings were contrary to these findings and, therefore, disproved the involvement of pseudoneglect.

General discussion

The first objective of the present study was to examine the impact of the side of the leading foot to step through a doorway on the directional bias in the upper-body midpoint while walking through a doorway. All three experiments clearly demonstrated that the foot used to step through a doorway strongly influenced the directional bias of the upper-body midpoint. Figure 4 shows that the upper-body midpoint could shift to the side by approximately 50 mm depending on the side of the leading foot.

Precise swing limb placement contributes to more stability during the rest of the stride (Patla 2003). However, swing limb placement becomes unstable due to higher walking speed or neuromotor noise (Souman et al. 2009); as a result, a walking trajectory can fluctuate to the side, causing collisions with a narrow doorway. It is, therefore, necessary to manipulate these motor factors to examine any attentional/brain factors that may cause collisions with a narrow doorway.

Despite the strong effect of the placement of the leading foot, however, the present findings provide some evidence that the upper-body midpoint deviated from the center of a doorway for other reasons. The present study replicated the findings by Nicholls et al. (2007, 2008) in that, independently of the impact of the leading foot, movement of one hand caused deviation of the upper-body midpoint to the contralateral side (Experiment 2). The key finding was that covert visual attention to one side of the door similarly caused deviation of the upper-body midpoint to the contralateral side (Experiment 3). This was contrary to the previous studies demonstrating pseudoneglect in a line bisection task (Milner et al. 1992; Nichelli et al. 1989), which demonstrated that the bisected point deviated toward the ipsilateral side of visual cueing. Instead, the present findings were likely to be consistent with the attentional cueing hypothesis. According to the hypothesis, movement of the hand and a visual stimulus serve as an attentional cue and are effective to avoid neglect of the ipsilateral side; as a result, the body midpoint is deviated to the contralateral side.

Although the involvement of attentional factors was suggested, the present study showed lack of a significant correlation between the directional bias in the walking task and the directional bias in the bisection tasks, for both the stimulus located in near space (Experiment 1) and that in far space (Experiment 2). This suggests that there seems to be no strong relationship between these two tasks. One factor limiting this suggestion was that we failed to show a tendency toward pseudoneglect in the spatial bisection task, i.e., a leftward bias in near space and a rightward bias in far space (Longo and Lourenco 2006; Gamberini et al. 2008; Lourenco and Longo 2009). Instead, we showed a significant leftward bias in Experiment 2, wherein the participants bisected a doorway-like stimulus located in far space. The result of the leftward bias despite the stimulus being located in far space could have been an artifact of the use of a computer mouse for bisection. In other words, the manipulation of an arrow projected on a screen by the computer mouse may have led to a representation of the doorway stimulus as the stimulus in near space. Nevertheless, we showed a lack of correlation between both tasks.

Several studies testing cognitively intact individuals (Thomas et al. 2009; Nicholls et al. 2007, 2010) and neglect patients (Punt et al. 2008; Grossi et al. 2001) also reported a lack of strong relationship between a locomotor task and a bisection task, although some studies reported a significant correlation (Nicholls et al. 2008; Turnbull and McGeorge 1998; Berti et al. 2002). Thomas et al. (2009) showed no correlation between asymmetrical collisions during a computer-based root-following task and the directional bias in a grayscale task, which have been used as a measurement of pseudoneglect in several previous studies (Mattingley et al. 2004; Nicholls et al. 1999). Punt et al. (2008) reported that at least some patients who showed marked difficulties in finding targets on the left side or in avoiding obstacle on the left side when performing a walking task did not show unilateral spatial neglect in the traditional paper-and-pencil tests, such as line cancellation or letter cancellation.

Considering these previous reports collectively, the relationships of directional biases observed in both tasks are not likely to be strong. A possible explanation for the lack of strong relationships would be that even though the directional biases themselves were derived from the same mechanism, task-specific factors for locomotion, particularly motor factors, modify the performance of a walking task.

Nicholls et al. (2010) reported consistent rightward biases in locomotor trajectories when cognitively intact participants maneuvered an electric wheelchair or a scooter (but not a manual wheelchair) to pass through a doorway. The present findings were partly consistent with those by Nicholls et al. in that some participants showed rightward deviation regardless of which foot was used to step through the doorway (Experiment 1). However, a robust rightward bias was not observed in other experiments. In fact, the rightward biases observed in Experiments 2 and 3 were fully explained in line with the interactions between the effect of the leading foot and the effect of hand movement (Experiment 2) or the visual cueing (Experiment 3).

The reasons for the lack of agreement between the study by Nicholls et al. (2010) and our present study are unclear. Given that the participants in Experiments 2 and 3 were asked not only to aim at passing through the center of a doorway but also to move their hand (Experiment 2) or to covertly attend to one side of the door (Experiment 3), increased task difficulty in both tasks may have caused the lack of a consistent rightward bias. It could be argued that a consistent rightward bias was observed in Nicholls et al. (2007, 2008), despite the fact that their participants were also asked to move their hand while walking. A critical difference between their studies and ours was that the participants in Nicholls et al. did not aim to pass through the center of a doorway; their participants aimed simply at shooting a target (Nicholls et al. 2007) or manipulating a cell phone (Nicholls et al. 2008) while crossing. Our participants were aware that their primary goal was to aim at passing through the center of a doorway, and any additional secondary goal of moving their hand or covertly attending one side of the door should have increased the task difficulty. Future study should address this possibility.

It is also important to note that Nicholls et al. (2010) tested novice wheelchair users (and probably novice scooters), and their choice of participants could have affected their results (Higuchi et al. 2004, 2006, 2009a, b; Higuchi et al. in press). For example, able-bodied novices in manual wheelchair use perceived that a wheelchair increases both the width of the person-plus-wheelchair and the space required for passage without a collision. However, they tended to underestimate precisely how much space was required to maneuver a wheelchair through a doorway, even after several days of practicing performing this behavior (Higuchi et al. 2004). However, experienced wheelchair users (patients with tetraplegia who had several years of experience using a wheelchair) not only accurately perceived how much space was required to pass through an aperture while using their own (familiar) wheelchairs but also while using wider, less familiar wheelchairs (Higuchi et al. 2009b).

Moreover, gaze patterns were completely different when able-bodied participants walked through a narrow doorway and when the same participants used a manual wheelchair to pass through the doorway (Higuchi et al. 2009a). These findings suggest that extensive experience in locomotor form can affect the spatial perception and cognition for locomotion. As noted earlier, because Nicholls et al. (2010) tested novice wheelchair users (the amount of practice before the experiment was not described), it is possible that lack of experience in using a wheelchair may have affected their results. This possibility also needs to be addressed in future studies.

In conclusion, the present study demonstrated that the directional bias in locomotor trajectories while passing through a doorway results from the combination of motor factors, particularly the choice of the leading foot, and attentional/brain factors. It is therefore indispensable to quantify and discount motor factors before evaluating the involvement of attentional/brain factors on a directional bias. Attentional cueing is likely to be a plausible attentional function to lead to the directional bias in the body during walking.

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