Perception of spatial requirements for wheelchair locomotion in experienced users with tetraplegia

Takahiro Higuchi[1], Nao Hatano[2], Koichi Soma[2], & Kuniyasu Imanaka[1]
[1] *Department of Health Promotion Science, Tokyo Metropolitan University, Tokyo, Japan*
[2] *Kanagawa Rehabilitation Hospital, Kanagawa, Japan*
<Contact Email address; higuchit@tmu.ac.jp >

Abstract

This study investigated whether prolonged experience in navigating with a wheelchair results in enhanced perceptual abilities in estimating space required for wheelchair locomotion. In experiment 1 experienced tetraplegic patients, who lacked somatosensory inputs from the upper-limbs, and inexperienced, able-bodied controls judged whether a door opening of various widths was passable in a wheelchair. The patients were accurate in judging a passable opening for familiar and unfamiliar wheelchairs, whereas the controls underestimated spatial requirements for a wheelchair. These results were replicated in experiment 2 under which they observed an opening while their trunk was rotated. No effects of the trunk rotations indicated that mental image of the body, which are likely to be susceptible to the somatosensory deficits, were not involved in the judgment. Collectively, experienced wheelchair users with tetraplegia are able to represent the relationship between space and the 'body-plus-wheelchair' system despite the somatosensory deficits.

The objective of the present study is to investigate whether long-time wheelchair users with disabilities in the upper and lower limbs as a result of spinal cord injuries (tetraplegia) show excellent perceptual ability in judging a narrow opening as passable or not in a wheelchair.

We have previously demonstrated that, when inexperienced, able-bodied participants used a wheelchair, they were unable to accurately estimate spatial requirements (Higuchi, Takada, Matsuura, & Imanaka, 2004). They often determined that an impassable door opening was passable (underestimation of spatial requirements). Their underestimation was not completely eliminated after a moderately long, 8-day practice period in which they tried to go through a door opening of various widths in a wheelchair. This was in marked contrast with an individual's excellent ability to adapt to artificial extensions of body dimensions while walking (Higuchi, Cinelli, Greig, & Patla, 2006; Hirose & Nishio, 2001; Mark, Balliett, Craver, Douglas, & Fox, 1990). A plausible explanation for the marked contrasts in the rate of adaptation to artificial extension of body dimensions between walking and wheelchair use could be the differences in the degrees in expertise. Since the biomechanical features of locomotion change dramatically from walking to wheelchair use (e.g., upper-limb propulsion, restricted mobility, and changes in the position of the center of mass and base of support), extensive practice may be required to adapt to artificially altered body dimensions.

To confirm whether prolonged experience in navigating with a wheelchair results in accurate perceptual adaptation to a wheelchair, the present study tested the ability of experienced but *disabled* wheelchair users to estimate spatial requirements for wheelchair locomotion. This is important to test because some disabled wheelchair users, such as tetraplegic patients, experience perceptual as well as motor deficits in the upper and lower limbs. Somatosensory inputs from the upper limbs while grasping the hand rims of a

wheelchair are usually the most powerful source for obtaining information about the dimension of a wheelchair and body posture while using it. It is therefore far from clear whether, despite the lack of somatosensory inputs from the upper limbs, prolonged experience in navigating with a wheelchair lead tetraplegic patients to acquire enhanced perceptual ability in estimating the spatial requirements for wheelchair locomotion. The rationale for conducting the present study by testing those with tetraplegia is to clarify these issues.

General Methods in Experiments 1 to 2

Participants
Eight experienced wheelchair users with tetraplegia participated in a series of experiments as the tetraplegic group of participants. The lowest segment of the intact spinal cord was determined on the basis of Zancolli's classification (Zancolli, 1979). In this classification, the experimenter specified the lowest functioning segment of the spinal cord by examining whether or not joint movements at the elbow, wrist, and fingers were normal in function. Every participant in the tetraplegic group was classified into the C6 level. Eight able-bodied people who had never used a wheelchair before, matched in gender and age to the tetraplegic group, volunteered to participate in the control group.

Apparatus
A door opening was made with two pieces of a thick black curtain (1.2-m wide× 2-m high). The opening was placed 2 m in front of the back wall of the room. A standard manual wheelchair (Rollstuhl, Tokyo, Japan) was used. The wheelchair was 43.5-cm high at the seat pan and 64-cm wide. Participants also used their own wheelchairs. The widths of their wheelchairs averaged 60.0 cm (ranged from 56 to 62 cm). The participants of the tetraplegic group were tested in a 9.0 m × 6.0 m room in the Kanagawa Rehabilitation Hospital, while those in the control group were tested in an 8.0 m × 3.8 m room in Tokyo Metropolitan University.

Experiment 1

Methods

Task & Procedure
The experimental task was to make a determination from a 2.8-m distance as to whether a presented door opening was passable or impassable (see Figure 1). Determinations were made for two forms of locomotion (usual or new). The usual form of locomotion refers to the use of an individual's own wheelchair in the tetraplegic group and walking in the control group. The new form of locomotion refers to the use of an unfamiliar wheelchair in both groups. To determine whether a space was passable in a wheelchair, the participants sat in the assigned wheelchairs and made a determination under the following condition: they were allowed to reposition their arms to reduce their spatial requirements; however, they had to continue to grasp the handrims when they passed through the door opening. For the control group to determine whether a space was passable when walking, they sat in a chair with a height of 43.5-cm and made a determination under the condition that they were not allowed to rotate their shoulders when crossing the opening. During the estimates, the participants were free to move their heads, bodies, and arms, but they could not stand up from their chairs or wheelchairs.
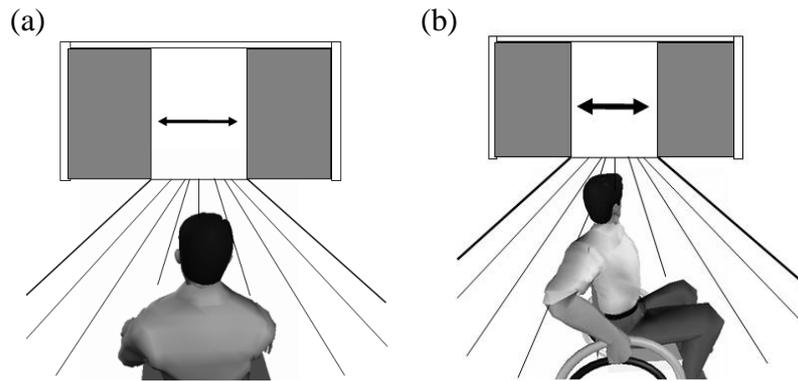
Figure 1. A setup in Experiments 1 (a) and 2 (b). A participant determined from a 2.8-m distance whether he could pass through a presented opening without collision. In Experiment 2 the task was performed while rotating their trunk in the yaw dimension.

The participants performed the visual estimation task three times under each locomotion-form condition. The first one was conducted prior to any experience in passing through openings (pre-practice phase). The other two were conducted after ten practice trials of passing through openings in each case (the post1- and post2-practice phases). In each phase, a series of opening widths was presented to the participants with the method of limits. In this method, a series of widths for the opening was presented in either an ascending (e.g., 40, 45, 50 cm) or descending (e.g., 90, 85, 80 cm) order with consecutive intervals. The presentation of the series of opening widths was terminated when the participants gave two successive affirmative (i.e., passable) responses in the ascending series or two successive negative (i.e., impassable) responses in the descending series. Each participant performed two ascending series and two descending series in each phase.

Dependent variable: Relative perceptual boundary.
A dependent variable was the ratio of the perceptual boundary between passable and impassable widths to the minimum passable widths. This was termed "relative perceptual boundary." To obtain the perceptual boundary from each participant for each phase, the psychometric function was plotted, indicating the proportion of passable judgments (y-axis) as a function of opening widths (x-axis). Each psychometric function was fitted by a logistic function, in which the best-fitting function was obtained on the basis of the least-squares method. The perceptual boundary was defined as the value on the x-axis at which the function passed through the 50 % level. The relative perceptual boundaries were analyzed in a Group (tetraplegic and control) × Locomotion-form (usual and new) × Phase (pre, post1, and post2) analysis of variance (ANOVA) with repeated measures on Locomotion-form and Phase.

Results and Discussion

The mean relative perceptual boundaries obtained from the three phases (pre, post1, and post2) under each locomotion-form condition in the tetraplegic and control groups are shown in Figure 2. A significant interaction between group and locomotion-form (F (1, 14) = 22.8, MSE=0.02, $p < .01$). Multiple comparisons indicated that the relative perceptual boundaries under the new-form condition for the control group were significantly smaller than those under the usual-form condition for the control group and under the two locomotion-form conditions for the tetraplegic group.
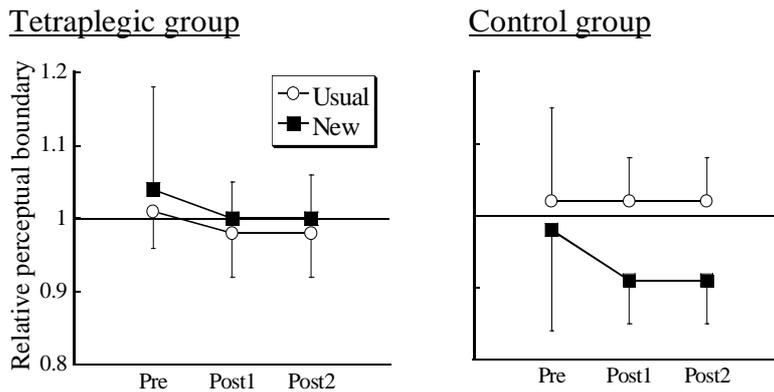
Figure 2. The mean relative perceptual boundaries obtained from three phases of the usual- and new-form conditions in the tetraplegic and control groups in Experiment 1.

The relative perceptual boundaries in the tetraplegic group were very close to 1.0 for both the usual and new conditions. Their estimates under the new-form condition were accurate in the pre-practice phase, in which the participants had never experienced passing through door openings in an unfamiliar wheelchair. These results indicated that, despite their somatosensory deficits, the tetraplegic participants adapted well to their spatial requirements for wheelchair use even when they used a wheelchair that they had never used before.

Experiment 2

In the second experiment, the participants performed the same estimation task as in the first experiment while rotating their trunk in the yaw dimension (i.e., changing the angle of his/her trunk relative to a door opening). We examined the effect of yaw trunk rotations to investigate the involvement of the mental image of the body/wheelchair in the perceptual ability to estimate the space required for locomotion.

Methods

The participants performed the same judgment task as in the first experiment. The differences in the procedure between the first and present experiments were summarized as follows. Under each locomotion-form condition (i.e., usual and new), the task was performed under three yaw trunk rotations (0, 45, or 90 deg). Trunk rotations were introduced in only one direction (clockwise or counterclockwise). Unlike Experiment 1, a practice phase of moving through a door opening was not introduced. It was because no significant effects of the practice were found Experiment 1. The relative perceptual boundaries obtained for the respective rotation angle of the trunk under each locomotion-form condition were analyzed in a Group ×Locomotion-form × Rotation analysis of variance (ANOVA) with repeated measures on Locomotion-form and Rotation.

Results and Discussion

The mean relative perceptual boundaries obtained from each of three trunk rotations under the usual- and new-form conditions for the two groups are shown in Figure 3. The main effect of form was significant (F (1, 14) = 8.9, MSE=0.05, $p < .01$), showing that the relative perceptual boundary under the new-form condition was significantly smaller than that under

the usual-form condition. The significant interaction between group and form (F (1, 14) = 22.6, MSE=0.12, $p < .01$) showed that the relative perceptual boundary for the control group was lower under the new-form condition than under the usual-form condition, and that the boundary under the new-form condition was lower for the control group than for the tetraplegic group. No significant effect of rotation was found (F (2, 28) = 0.69, MSE=0.01).

It was surprising that no significant effects of yaw trunk rotations were found in either the tetraplegic or control group. It would seem that, regardless of whether the mental image of the body is intact or not, the participants were not involved in rotating of the mental image of their body/wheelchair while performing the task with yaw trunk rotations. One possible explanation for the findings would be that the perceptual information about the body/wheelchair used as a reference frame in estimating spatial requirements for locomotion and that used for creating a mental image of the body/wheelchair is independent from each other. If this explanation is true, then a tentative conclusion would be that the lack of somatosensory awareness of the hand observed in the tetraplegic patients may have had an effect on the creation of the mental image of the wheelchair but not on the development of an internal frame of reference for the wheelchair; that is why prolonged experience in navigating with a wheelchair led tetraplegic patients to have excellent perceptual ability to determine whether a narrow space was passable or not in spite of the somatosensory deficits.
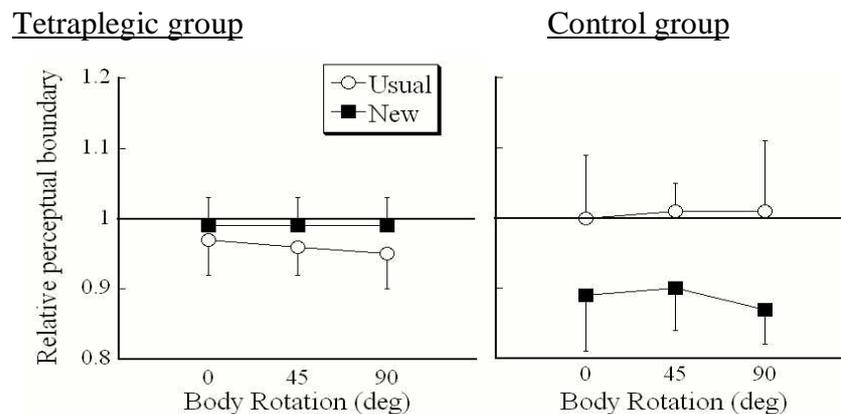

Figure 3. The mean relative perceptual boundaries obtained from three phases of the usual- and new-form conditions in the tetraplegic and control groups in Experiment 1.

General discussion

The results of Experiments 1 and 2 indicated that prolonged experiences with wheelchair use led tetraplegic patients with somatosensory deficits to have enhanced perceptual ability to estimate the spatial requirements of using a wheelchair. They made accurate estimates from their own wheelchairs and from unfamiliar ones. This was in marked contrasts to the results achieved by the able-bodied control participants, who underestimated their spatial requirements while using a wheelchair. These findings make it possible to conclude that a quick adaptation to artificially altered body dimensions while maneuvering external objects may occur in a short time only when an individual is practicing a well-learned, familiar activity.

The relative perceptual boundaries obtained from the tetraplegic patients in Experiments 1 and 2 were very close to 1.0 and even smaller than 1.0 when they their own wheelchair in Experiment 2 (we confirmed that the boundaries obtained in Experiment 2 were not significantly different from 1.0 when no trunk rotation was introduced). These results

suggest that the tetraplegic patients prefer estimates that leave a very small margin of safety. Similar results were obtained from able-bodied participants that were well trained in wheelchair use (Flascher Shaw, Kader, & Aromin, 1995) and from children who used a wheelchair due to cerebral palsy (Savelsbergh, Dekker, Vermeer, & Hopkins, 1998). Such estimation may be preferable because the overestimation can provide them with an extremely large cost for wheelchair locomotion. When wheelchair users determine that an opening is too narrow to cross, they must take a detour. Because taking a detour would have an extremely large effect on reaching the desired destination, they cannot afford to overestimate the space for locomotion. This potentially large cost resulting from the overestimation is significant compared to the extremely small cost resulting from the overestimation in the case of walking. When walkers determine that an opening is narrower than their body, they only have to rotate the shoulders to reduce the spatial requirements. Because the rotation has a relatively small cost, a walker will prefer the overestimation to support safe locomotion (Higuchi et al., 2004; Lee, Harris, Atkinson, & Fowler, 2001; Warren & Whang, 1987). This is why the preferable safety margin may be different depending on the form of locomotion (see Wagman and Taylor, 2005, for similar findings demonstrating the underestimation of spatial requirements when participants walked while holding a long T-shaped bar, under which the rotation of the shoulders did not contribute to reduce the spatial requirements).

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