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An Experiment to Detect Changes in Balance Perception Accompanying Balancing Task

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Abstract: In this study, we focused on the changes in balance perception accompanying balancing tasks. The study goals were to propose an experimental method in which subjects experience perceptual changes in balance from a seated posture and present evidence that such changes occur. As balance perception, we considered a psychologically upright posture, a posture at which the upper body feels slanted to neither the left nor right. For the experiment, we newly constructed a special stool. Dynamic environment on this stool with 2 DoFs, the lateral translation and the roll rotation, could change this psychologically upright posture after motor learning in a balancing task.

Keywords: human motion measurement, balance perception, perceptual change, balancing task

1. INTRODUCTION

It is not difficult for healthy persons to maintain their balance in static environments. Furthermore, humans can maintain their balance in dynamic environments by performing balancing movements [1, 2]. These balancing movements can sometimes occur with changes in perception. For example, some people can continue to experience seasickness on land; they perceive that the ground sways even though they are no longer on a ship, but are on the ground.

Perceptual adaptations accompanied with motor learning have been reported regarding somatosensory perception in learning paradigms involving arm-reaching movements [3]. However, our hypothesis is that such perceptual adaptations can be observed with other movements. Therefore, we examined perceptual changes in a balancing task. Our goals for this study were to identify and quantitatively evaluate changes in balance perception and develop an experimental method that evokes perceptual changes in balancing tasks.

2. DESIGN OF EXPERIMENT

2.1. Outline

Some environmental factors are related to perceptual adaptations. Identifying some of these factors would allow us to examine the mechanisms of perceptual adaptation in human motor control. We consider that these environmental factors should have the following characteristics:

1. Environment changes with some periodicity or regularity.
2. An individual can use motor learning to compensate for the influence of the environmental changes.
3. An individual can use these learned motor responses over long periods.

Here, we aimed at presenting environmental factors with the above characteristics to evoke perceptual changes in balance.

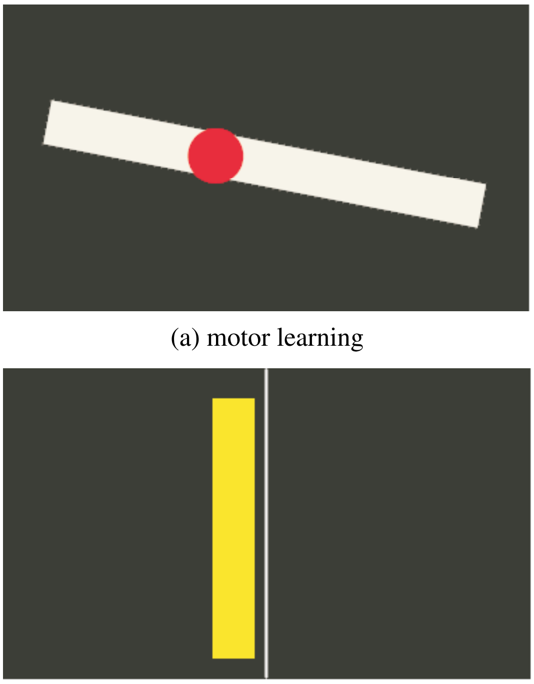
One behavior that differs between humans and most animals is an upright posture. Accordingly, the balancing experiments should be performed with standing subjects. However, considering special circumstances, such as a laboratory experiment, upright standing makes subjects susceptible to turning over. Because subjects should be secure during the experiment, they should be seated during the balancing experiment.

With balance perception, we focus on an upright posture. This is a psychological evaluation because it can deviate from the physically upright situation. Here, the psychologically upright posture is defined as the evaluation of balance perception. This evaluation is quantified as the deviation from a standing position. In experiments, the psychologically upright posture should be compared before and after the motor learning balancing task; the change in balance perception is quantified as the transition among these postures. To simplify the measurement, analysis, and discussion, the balancing experiments, including the motor learning and perceptual tests, were restricted in the lateral plane.

2.2. Motor learning

As mentioned above, periodic or regular changes in the environment are important to promote perceptual changes and motor adaptation. To create these environmental conditions in a balancing task for seated subjects, we introduced a stool with a seat that could rotate and was controlled at an arbitrary angle. Using this stool, we created an unstable condition for the subjects. To create a periodic environmental change, we regularly made a virtual shift of the rotation axis of the seat surface by modifying

† Satoshi Ito is the presenter of this paper.



(a) motor learning

(b) perceptual test

Fig. 1 An example of the images on HMD.

the control method. To maintain balance and keep the surface horizontal, the subjects had to adjust their posture so that the Center of Pressure (CoP) is always on the virtually shifting rotation axis of the seat surface. Additionally, an inertial force was applied as a perturbation by sliding the stool horizontally. This stool movement was presented in synchrony with the seat rotation; thus, both were regarded as periodic environmental changes. Because we restricted motion to the lateral plane, the entire stool was slid in the subject's lateral plane, and the rotation of the seat surface took place around their roll axis.

In the experiments, we asked the subjects to keep the seat horizontal to maintain their balance. Consequently, subjects learned trunk movements that maintained both balance and seat surface level with respect to the periodic external perturbation.

In some pilot tests, it was difficult for some subjects to recognize how much of an angle the seat surface was tilting. Thus, we provided information on the surface tilt angles to the subject by drawing the angles with computer graphics (CG).

In other pilot tests, the seat position was presented with a monitor display placed in the laboratory. However, we recognized that the results of our perceptual test (next section) were affected by the visual information presented on this monitor: the direction of the upper or side edge of the monitor could be effective to judge which side the body was slanting. Namely, the monitor was a stationary object in the laboratory that could serve as a landmark and enable visual correction for detecting the body orientation in the seated posture. Thus, by introducing a head-mounted display (HMD), we eliminated the effect of visual information, as in the closed-eye situation, by restricting it to the HMD monitor image. This has an advantage in that the HMD image does not move, even if the subjects nod or twist their neck because the HMD image moves together with the head.

2.3. Balance perceptual test

The motion and perception was restricted in the lateral plane. Thus, we asked the subjects to adjust the posture in their lateral side to achieve some specific target postures. Thus, we evaluated their psychologically upright posture, the posture feeling just upright.

To indicate the target posture to the subjects, we used the CG image. The cursor moving with the body's slant was displayed together with the target position. The subjects were asked to manipulate this cursor by slanting their body at the seated posture, and to stop and keep the cursor at the target position. As is the same with motor learning, HMD was utilized to remove other visual information than the CG images on the HMD screen.

The psychologically upright posture can be rephrased as a posture where subjects recognize that they are slanting to neither the right nor the left. In other words, it is the posture at which the possibility of the subject's feeling of slanting to the right or left is equal. Accordingly, we asked the subjects to change their posture many times to some types of non-upright postures; we asked them to answer the question "to which side are you feeling a slant?" Based on their answers, we found out that the probabilities of the answers of "toward the left" and "toward the right" remained the same, i.e., 50% each. This posture was quantified as the psychologically upright posture.

3. METHODS

3.1. Experimental setups

We constructed a special stool with three AC motors: one motor operated the horizontal sliding movement and the other motors rotated the seat surface of this stool. The tilt angles and horizontal movement were detected by the rotary encoder equipped in the AC motors. Four load cells were set at each corner of the seat surface. These load cells provided the position of CoP on which the subjects put their weight for maintaining the balance on this stool. Around this stool system, fences covered with mattresses were built to ensure the safety of the subjects if they tumbled.

A 3D real-time motion capture system was used to measure the horizontal deviation of the subjects' body. Two cameras were fixed up above in front of the stool. The spatial error in this measurement environment was 0.2 cm at the maximum.

A personal computer operated by Art-Linux with an A/D and a D/A converter board and encoder counter board was used to control this stool system. The signals from the rotary encoder in each AC motor were connected to the encoder counter board to detect the tilt angle of the seat surface and the horizontal movement of this stool. The signals from each load cell were inputted to the A/D converter board after being amplified at the sig-

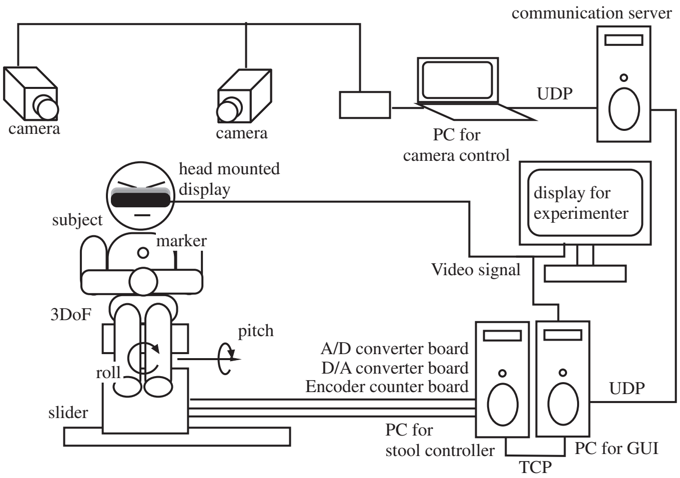


Fig. 2 Construction of experimental setups.

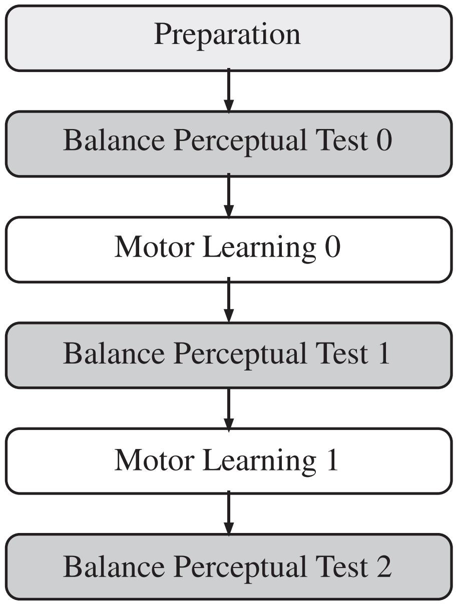


Fig. 3 Procedure of the experiment.

nal conditioner. These load information gave the position of CoP. Using the sensory information, the driving force necessary to control the stool position was calculated, and then, the corresponding voltage signals were outputted from the D/A converter to the motor drivers supplying the necessary power from the commercialized AC power source. The duration of this control routine was 1 ms.

Data from a motion capture system was sent to this control PC via the server PC using UDP protocol. To distribute the computational load, another PC operating with Art-Linux was used to draw CG on HMD. This PC was connected to the control PC by a 20ms TCP protocol. This PC also provided GUI to control a control panel that the experimenter used in the experiments.

The experimental system is depicted in Fig. 2.

3.2. Motor learning phase

Subjects were asked to sit on a stool so that the stool slid in their lateral direction. The rotation of the seat surface around the pitch axis was fixed so that the seat surface was horizontal in the initial state. Conversely, the seat rotation around the roll axis was driven by the position of CoP. The driving torque was generated toward the deviated direction, and its magnitude was proportional to the deviation of CoP from the virtual pitch axis. For example, if CoP deviated to the left, the seat surface rotated to the left; the seat became unstable. Regarding the virtual rotation axis, we could set it with the control panel in an arbitrary position. To maintain the seat surface horizontally, the subjects had to move CoP on the virtual roll rotational axis and maintain that position.

In the motor learning phase, the virtual rotation axis also shifted in phase and in the same direction of the stool's horizontal slide. For compensating the inertial force by the lateral slide of the stool, the subjects had to slant their upper body in the proceeding direction and move their CoP in the same direction to track this shift of the virtual rotation axis.

The CG image in Fig. Fig. 1(a) was displayed on HMD to let subjects know the information on the tilt of the seat surface as well as the position of the virtual rotation axis. The gray bar rotated in synchrony with the seat surface angle, and the large red circle denoted the position of virtual rotation axis on the stool. The color of the bar turned yellow from gray when the tilt angle was less than 8 degree. The subjects were instructed to keep the color of this bar yellow.

When the movement of the stool finished, the stool went back to the starting position. While moving to the starting position, the stool was controlled in the reverse manner. Those are all stool movements in one trial of the motor learning phase. In the motor learning phase, the subjects repeated this trial many times to learn a new motion pattern for balancing under a newly given environment.

3.3. Perceptual test phase

The balance perceptual tests were performed in a static environment by locking the motion of the motors. The subjects were instructed to sit still in the same place as in the motor learning phase, and achieve a target posture by slanting the body to the left or the right, based on the HMD image shown in Fig. 1(b). A marker was attached on the upper body part of the subjects, and the marker's position was monitored by the motion capture system. A yellow bar with a 20-pixel width (Fig. 1(b)) moved in accordance with this maker. The 1 pixel-width white line displayed at the center of the monitor became the target position for the bar. When the bar overlapped the white line, it bar turned red. The subject was then required to maintain the posture so that the center of the bar stayed at the white line.

The movement of the bar was synchronized with that of the marker, but the bar did not always move to the target position on the white line when the subject posture was just upright. The relation between the center

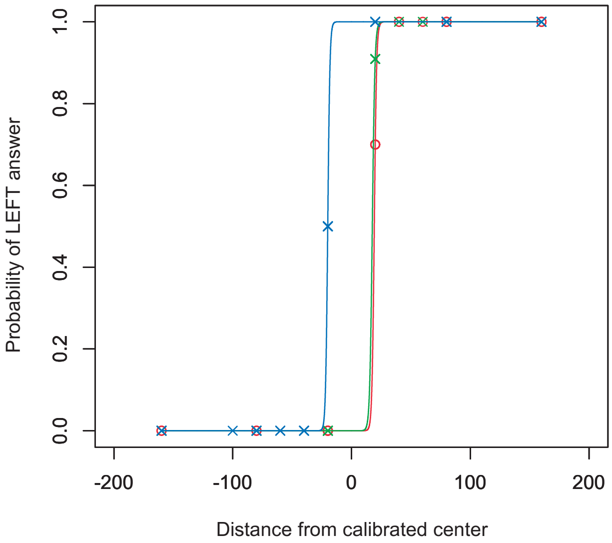


Fig. 4 Psychometric Function approximating the data with logistic function.

position of the bar and the subject's upright posture was different from question to question. Namely, the posture that the subject was asked to maintain was not necessarily upright. Then, at the target posture, we asked the subjects to answer the question, "to which side are you feeling a slant, Left or Right?"

After the subjects answered this question, the stool slowly oscillated 1 cm in the lateral direction for 3 s, to refresh the postural sensation of the subjects. During this period, the yellow bar in the HMD screen stayed at this center position. Then, a new relationship between the position of the yellow bar and that of the marker was redefined for the next test.

The subjects had to repeat many questions with the same or different relationship between the bar and marker positions. Based on their answers, the psychologically upright posture was quantified in a statistical manner.

3.4. Procedure

Before the experiments, the subjects were instructed to sit at the center of the stool, not lean against the safety fence except in an emergency, and push the emergency switch only when the experiment had to be stopped because of any sickness.

The experiment began with the initial setting of the motion capture system, which determined the relationship between the subject's posture and the center of the HMD screen. Next, the first perceptual test 0 was performed. After the first learning phase, motor learning 0, the second perceptual test 1 was run. Then, the third perceptual test 2 followed motor learning 1. These procedures are summarized in Fig. 3.

All three perceptual tests were performed in the same experimental condition. The HMD scale was set as 0.25 mm/pixel (40 pixel/cm). The origin of this scaling, in other words, the relationship between the yellow bar and the position of the marker in the actual experimental space was given adaptively according to the answers by subjects. The results are described using this pixel value of bar -display deviation on the HMD screen where the bar was displayed to the right from the initial values set at calibration: The -40 value, for example, indicates that the bar was displayed 40 pixels to the left, and thus the subjects actually had to slant 10 mm to the right from the calibrated position to bring the bar to the target position. Regarding the algorithm to determine the bar-display deviation, PEST [4] was adopted. A total of 6 PEST ran with the initial value of ±160 pixels (±40mm), and the initial step size was 80 pixels (20 mm) and the minimal step size was 20 pixels (5 mm). We confirmed that the subjects had not changed the seat position because it was a critical factor to evaluate the posture measurement.

To make motor learning 0 a control experiment, its experimental conditions were selected such that no other motor learning took place. The subjects were told to sit at the same place and wait for 10 min, the average time of motor learning 1, without doing anything.

In motor learning 1, the subjects were asked to maintain the seat surface of the stool in a horizontal position (see section 3.2). The sliding distance of the stool was 20 cm, the distance of the virtual axis shift was 2.5 cm, and the time of the sliding as well as the axis shift was 5 s (movement for 4 s and stop for 1 s) in a one-way direction. We ran 100 trials per subject.

We recruited 14 subjects: 7 were included in left directional motor learning and 7 for right directional motor learning. The experimental conditions for these two groups differed only in the starting direction of the sliding of the stool and the shift in the virtual axis. This experiment was approved by the ethics committee being set up in Graduate school of Medicine, Gifu University (25-234). All subjects had signed an informed consent form after they were provided with an explanation of this experiment.

3.5. Analysis

In the balance perceptual test, we recorded several answers at each bar-display deviation. These answers represented the subjects' sense to which side they were feeling the slant at several targeted postures. These postures included the same postures; however, the subjects did not always give the same judgment about the left or right slant. This judgment was easy when the slant angle was large, but it was not so easy if this angle was small and the posture was almost upright.

We defined the psychologically upright posture as the posture at which the subjects' answer was 50% right and 50% left. Therefore, we estimated the probabilities of the subject's answer that the slanting side was the left side at each posture, and then, the probabilities were approximated using a logistic function to construct a so-called psychometric function. We quantified the psychologically upright posture as 0.5-point of the psychometric function because the probability is the same at the left and right sides.

The values obtained from three perceptual tests for each subject were statistically analyzed. The averages

Table 1 Perceptually quantified upright postures (by pixels).

	TEST0	TEST1	TEST2
L1	19.62	20.16	-6.99
L2	19.19	17.51	-20.0
L3	0.08	18.58	60.06
L4	28.35	29.49	4.06
L5	52.00	57.02	21.26
L6	-14.06	1.98	-5.31
L7	40.40	21.41	-13.79
R1	14.17	19.93	42.35
R2	18.58	17.51	43.02
R3	-10.48	-17.51	16.65
R4	19.35	16.65	20.16
R5	-2.57	-18.77	25.49
R6	-2.45	-8.47	32.83
R7	-20.16	-19.19	20.00

among the subjects were compared among three perceptual tests. If the averages had significant differences, we considered that motor learning affected balance perception, i.e., the perceptually upright posture had changed.

4. RESULTS

4.1. Sample answer from a subject

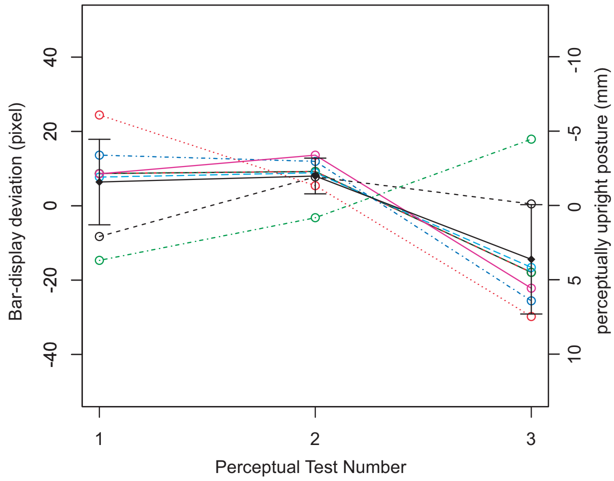
One set of answers obtained from a subject in the left directional condition is plotted in Fig. 4, where the balance perceptual tests 0, 1, and 2 are represented with red, green, and blue, respectively. These plotted points indicate the ratio of the "Left" answer in each bar-display deviation. These plotted points were approximated using logistic function. These graphs are also illustrated in Fig. 4.

In this subject, the shape and place of the graphs before and after motor learning 0 did not change at all, but the graph seemed to shift to the left after motor learning 1. The psychologically upright posture was evaluated as 0.5-threshold of this psychometric function, indicating that, in this subject, motor learning 0 had few effects on the psychologically upright posture, whereas motor learning 1 made a shift toward the right side of the psychologically upright posture, minus direction in this graph. In other words, this subject tended to regard the posture slanting to the right side as an upright posture.

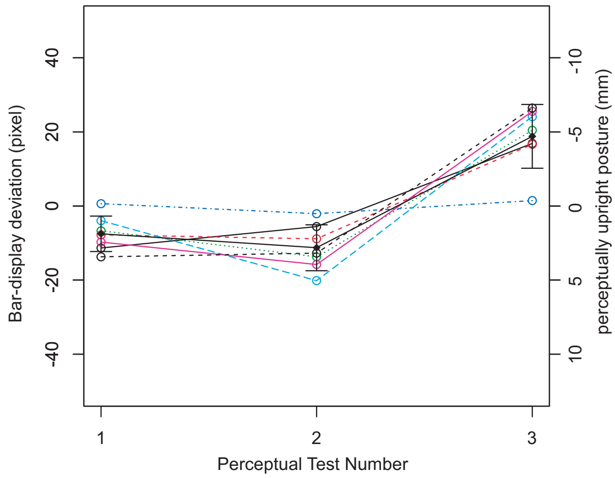
4.2. Psychologically upright posture

The calculation mentioned in the previous section was applied for all 14 subjects to obtain the psychologically upright posture. The results are summarized in Table 1. To remove the bias effect of each subject, the data were realigned so that the average of three perceptual tests would become zero in each subject, as depicted Fig. 5:(a) lists the subjects in the left directional condition in the motor learning phase, whereas (b) lists the subjects in the right directional condition in the motor learning phase.

For both Fig. 5(a) and Fig. 5(b), it can be considered



(a) Left directional condition.



(b) Right directional condition

Fig. 5 Transition of the perceptual upright posture, rearranged by zero average for each subject.

that the change in the psychologically upright postures before and after motor learning was small, whereas the change before and after motor learning 1 tended to be very large. It should be noted that the changed direction of the psychologically upright postures is reversed if the shifting direction of the stool is opposite.

4.3. Statistical analysis

Repeated measures ANOVA was used for the data in Table 1. The data contained six groups: three groups of L-TEST0, L-TEST1, and L-TEST2 for left directional motor learning, and R-TEST0, R-TEST1, and R-TEST2 for right directional motor learning. We found a significant difference among the averages of the psychologically upright posture ($p = 0.000643 < 0.01$).

Next, Tukey's test was applied to the data, as is indicated in the graph in Fig. 5; and the results are summarized in Table 2. There were no significant differences among L-TEST0, L-TEST1, R-TEST0 and R-TEST1. However, there were some significant differences between R-TEST0 and R-TEST2 and between R-TEST1 and R-TEST2 ($p < 0.01$), although there were no sig-

Table 2 Perceptually quantified upright postures.

	L-TEST1	L-TEST2	R-TEST0	R-TEST1	R-TEST2
L-TEST0	0.99776	0.23307	0.52024	0.22291	0.26419
L-TEST1	-	0.09829	0.27559	0.09314	0.50466
L-TEST2	-	-	0.99425	1.00000	0.00100**
R-TEST0	-	-	-	0.99290	0.00462**
R-TEST1	-	-	-	-	0.00093**

nificant differences among L-TEST0, L-TEST1, and L-TEST2. There was also a significant difference between R-TEST2 and L-TEST2 ($p = 0.00100 < 0.01$).

5. DISCUSSION

An example that motor learning affected perception was demonstrated in arm-reaching movement where somatosensory perception was featured. Under our assumption, such perceptual adaptation will usually take place during motor learning. Therefore, we investigated this phenomenon in the human balancing task.

We considered that periodicity of the environment is important to accomplish motor learning. To present this condition, we constructed a special stool with 3 DoF of motion. In the initial pilot tests, we provided a condition so that the seat surface rotated toward the orthogonal direction to the deviation of CoP. However, it seemed difficult for many subjects because the seat surface did not continuously remain horizontal. Fortunately, the improved, easier procedure adopted in this study seemed sufficient to provide the perceptual change in the balancing task. This task enabled the subjects to learn the trunk motion patterns with respect to periodic perturbation in an unstable situation. However, we did not evaluate the progress of motor learning. To investigate the mechanism linking motor learning and perceptual changes in a balancing task, analysis of motor learning will be one of our important future works.

Regarding the perceptual tests, we focused on a posture that subjects felt was upright. In this experiment, we shut out visual information using HMD. In addition, during the perceptual test, the body's movement for achieving the target posture was not so large, which implies that head movement was small; thus, the effect of the vestibular information seemed less. Therefore, the judgment may come from the positional information of the trunk. We need to clarify what kind of the sensory information is critical using the results of ongoing experiments.

6. CONCLUDING REMARKS

We conclude that a balancing task on a stool moving to the right with a right-shifting roll axis has an effect to change balance perception toward the opposite left direction. We could confirm significant differences before and after the left directional perturbation if we tested more subjects.

These results indicate that the experimental method we proposed can be a paradigm for demonstrating change of perceptual balance, although the balancing task was imposed in a seated posture.

In future studies, we will evaluate how much the subject learned in the balancing task and investigate the relationship with the amount of perceptual change.

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