



# Effects of the gravity direction in the environment and the visual polarity and body direction on the perception of object motion

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## ABSTRACT

To process the motion of objects, humans need to consider information about up-down direction as obtained through various cues such as the gravity direction in the environment, visual polarity, and body direction. This study investigates the effects of up-down direction, as obtained from these cues on motion perception, with a focus on acceleration perception. We presented the participants with moving objects that had various acceleration speeds and measured the physical acceleration to be perceived as constant velocity. We examined the effect of the up-down direction from the visual polarity by changing the relationship between the up-down direction indicated by the gravity direction cue and the up-down direction indicated by visual polarity by manipulating the posture of the observer. The results showed that the up-down direction received by the gravity affected motion perception. Moreover, the up-down direction indicated by the visual polarity affected motion perception when the observer's body direction and the physical gravity direction were different. On the other hand, up-down direction indicated by the visual polarity did not affect motion perception when the body direction coincides with physical gravity direction. Overall, the results suggest that the up-down directions indicated by the gravity, visual polarity, and body direction are integrated non-linearly in the perceived acceleration of visual motion.

## 1. Introduction

Earth's gravity affects the motion of all the objects we see in daily life by accelerating them toward the center of the earth. Therefore, to efficiently process object motion the human visual system needs to consider gravity. For example, when catching a falling object, a person attempts to predict its trajectory by taking the effect of gravity into account.

Several studies have explored how people perceive object motion with respect to the effect of gravity. For example, the direction of gravity affects a person's memory of the last seen position of a target that has disappeared (Freyd, 1987). When one observes a moving object, the memory of the final position of the object shifts forward in the direction of motion if the object disappears suddenly. The shift of this memorized position is larger for falling motion than for rising motion, and the shift is downward in the motion path in horizontal motion (Hubbard, 1995). The effects of gravity on perception are also reported

in implicit weight changes of an object due to its size (Hubbard, 1997) and three-dimensional motion (Nagai, Kazai, & Yagi, 2002).

Some studies have shown that the information about gravity based on visual information affects a person's behavioral response to a moving object. For instance, in Senot, Zago, Lacquaniti, and McIntyre (2005), observers intercepted a vertically moving ball at a particular position on the frontal parallel plane in a virtual reality environment. The ball moved with an accelerated, decelerated, or constant velocity. The participants' success rate increased when the velocity was accelerated in downward motion and decelerated in upward motion. This means that the observer's response was delayed with the upward motion and hastened with the downward motion. The researchers considered that the observer's response was based on experiences in real environments, in which objects move under the effect of gravity. Similar effects of gravity on motion perception have been reported in experiments with real environments (Lacquaniti & Maioli, 1989a,b) and motion in depth (Le Séac'h, Senot, & McIntyre, 2010).

Abbreviations: PSUM, Point of subjective uniform motion

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The direction of gravity can also be estimated from visual information, although the effect of gravity on the perception of motion, as described in the aforementioned studies, depends on signals from vestibular/somatosensory sensations. For example, it can be obtained from specific positional relationships, such as the sky and ground, and structural features, such as trees and houses (Runeson, 1988), which is known as “visual polarity” (Howard, 1982). Zago, Scaleia, and Miller (2011) reported that the gravity from visual information affects motion perception. They asked participants to intercept objects moving in a vertical direction on the frontal parallel plane with a background image of a basketball court. The participants’ success rate was higher when the direction of motion corresponded with the direction of the gravity in the visual background, regardless of the direction of the gravity in the real environment.

However, it is not clear whether motion perception itself changes with the information of gravity direction, because the tasks in previous studies depended on the memory of a moving object’s position or used action response and did not directly examine motion perception. Asano, Kaneko, and Mizushima (2008) reported that the gravity direction relative to motion direction affects the motion perception itself. They measured the positive/negative acceleration of a moving object when it was perceived as motion with constant velocity (uniform motion) by presenting a ball moving with acceleration in a vertical or horizontal direction on the frontal parallel plane. The results showed upward motion with a subjectively constant velocity had negative acceleration and downward motion with a subjectively constant velocity had positive acceleration. Horizontal motion was perceived as having constant velocity when it was actually at an almost constant velocity. In other words, positive/negative acceleration of motion perceived as constant velocity was consistent with the positive/negative acceleration produced by gravity. Calderone and Kaiser (1989) study on the discrimination threshold of acceleration showed there was no anisotropy in vertical motion on the frontal parallel plane. Although, Asano et al. (2008) and Calderone and Kaiser (1989) asked the observer to respond whether the moving stimulus on the frontal parallel plane appeared to have a positive or negative acceleration. However, the purposes of the studies were different from each other. Asano et al. (2008) measured the offset of physical acceleration for the perception of zero acceleration, whereas Calderone and Kaiser (1989) measured the threshold of positive acceleration and negative acceleration. It has been reported that human observers are typically very insensitive to motion acceleration (e.g. Zago, McIntyre, Senot, & Lacquaniti, 2009). The Weber fraction of acceleration discrimination is generally high and between 17% and 290% depending on the stimulus modulation waveform, frequency, and presentation time. However, the Weber fraction of velocity discrimination is better than 5%. Though humans do not accurately detect acceleration directly, they are able to perceive acceleration and deceleration by comparing the velocities of successive time windows (Werkhoven and Snippe, 1992). Aside from the sensitivity of acceleration, it is likely that detection of the difference in the subjective velocities would be affected by gravity direction. Because Asano et al. (2008) used a gray background, the effect of gravity from visual information was not revealed. Moreover, the question remains of how the cues that give information on gravity, visual polarity, and body direction, are integrated to contribute to motion perception.

It has been suggested that the perception of gravity or up-down direction is decided by the multi-sensory integration process of three sources of sensory information: gravity signal obtained from the vestibular/somatosensory senses, polarity of visual scene, and longitudinal body axis (Mittelstaedt, 1998, Jenkin, Jenkin, Dyde, & Harris, 2004, Harris, Herpers, Hofhammer, & Jenkin, 2014). For example, Jenkin et al. (2004) manipulated an observer’s posture and visual scene polarity and measured the perceived upward direction by using a stimulus with shading. As a result, they found that the perceived upward direction was determined by weighted linear combination of the three vectors of the gravity direction, the polarity of visual sense, and the

longitudinal body axis. The weights for the linear combination have been proposed to depend on the reliability of each cue. Similar results were also shown in the studies of subjective visual vertical (SVV) (De Vrijer, Medendorp, & Van, 2008, Vingerhoets, Medendorp, & Van, 2008, Clemens, De Vrijer, Selen, & Van, 2011) and of heading perception (see the review of Fetsch, DeAngelis, & Angelaki, 2010). However, it has not been clearly shown how the perception of gravity affects the perceptual bias of motion perception. One of the possible explanations would be that the directional information used for perception of up-down direction, SVV, and heading perception is also used for the perceptual bias of motion.

In this study, we measure the physical acceleration of motion perceived as constant velocity and calculate the point of subjective uniform motion (PSUM) in various motion directions on the frontal parallel plane. Next, we examine how the up-down direction obtained from different cues are integrated, since the gravity direction, visual polarity, and body direction, and each signal affects the behavior response (Senot et al., 2005, Lacquaniti & Maioli, 1989a, b, Zago et al., 2011).

The present study was based on the notion that three vectors of the up-down direction, body direction, the gravity and polarity of visual sense contribute to the direction of acceleration bias in motion perception. The physical gravity direction mainly detected by vestibular/somatosensory senses, is the primary information for perceived gravity direction. The visual polarity, the up-down direction in the visual content, can be the information for perceived gravity direction. The up-down (head-to-foot) direction along the body is also the information for the perceived gravity direction because the body axis is generally corresponding to the physical gravity. In Experiment 1, we investigated the effect of the physical gravity direction and body direction on PSUM by using a stimulus moving on the frontal parallel plane in one of four directions: up, down, left, or right. The background was uniform gray and did not include the information of gravity direction from the visual polarity. We expected there was a PSUM bias along the up-down motion direction because the gravity direction and body direction are consistent and corresponding to the up-down motion direction. In Experiment 2, we examined the effect of gravity information in a visual polarity by using the background of a natural scene. When the visual polarity indicated different direction from the gravity direction and body direction, we expected that the PSUM of the up-down motion direction would become less than that when the visual polarity indicated the same direction as those by the gravity direction and body direction. In Experiment 3, we investigated the magnitude of PSUM by manipulating the relationship among the gravity direction, the visual polarity, and body direction. When the gravity direction and body direction were inconsistent, we expected that the effect of visual polarity was greater than when they were consistent. As a summary, Table 1 shows the combinations of the downward direction by the body direction, the gravity direction and the visual polarity, and motion direction on the frontal parallel plane in Experiments 1, 2, and 3. Since the body, head, and retinal axes were not separated in this study, they were collectively treated as the longitudinal body axis. Details of the table will be explained in the Materials and Methods section for each experiment.

## 2. Experiment 1

To clarify how the acceleration bias of subjective uniform motion changes according to the direction on the frontal parallel plane, we measured the acceleration (acceleration bias) of motion with subjective constant velocity when objects moved to one of four directions, up, down, left, and right, on the display.

### 2.1. Materials and methods

#### 2.1.1. Participants and ethics

Nine observers, including two authors, participated in the

**Table 1**  
Combinations of body direction, physical gravity direction, visual polarity, and motion direction for Experiments 1, 2, 3a, and 3b.

Experiment	Experimental condition	Downward direction			Motion direction
		Body direction	The gravity	Visual polarity	
Exp1		↓	↓	—	↕
Exp2		↓	↓	↑	↕
Exp3a		↓	⊙	↕	↕
Exp3b		↓	←	↕	↕

The arrows indicate down as defined by gravity or the body direction (the direction of the foot is down). The visual polarity or motion direction on the frontal parallel plane represents direction presented as a stimulus. ⊙ indicates that the gravity direction is toward the back of the participant.

experiment (2 females, mean age = 29.2 (24–40) years). Except the authors, the subjects were naïve for the purpose of the experiment. All the participants had normal or corrected-to-normal vision. They gave written, informed consent to take part in the study. The protocols of all experiment in this study was approved by the Tokyo Institute of Technology Ethics Committee, in conformity with the Declaration of Helsinki on the use of human subjects in research.

**2.1.2. Visual stimulus**

The visual stimulus was animation created using numerical computation software (MATLAB, MathWorks) with a free add-on (Psychophysics Toolbox) running on a PC (MacBook Pro, Apple). The motion object in the animation was a circle with a radius of 0.5 cm with a constant acceleration on a uniform gray background. It moved in one of four directions (Up, Down, Left, or Right) through the center of the display. The size of the background was 28.6 × 28.6 cm and the viewing distance was 38 cm; therefore, the visual angle was 41.2 × 41.2 deg. The average luminance of the background was 1.33 cd/m<sup>2</sup> and that of the circle was 37.9 cd/m<sup>2</sup>. The average velocity of motion was 13.9 cm/s and the acceleration was varied according to

the participants’ response with the staircase method in the range of 6 cm/s<sup>2</sup> to −6 cm/s<sup>2</sup>. The total trajectory of the target was always 28.6 cm on the display. The average duration of the presentation was 2.13 ± 1.1 × 10<sup>−3</sup> s.

**2.1.3. Apparatus**

The stimulus was presented on a display (RDT233WX-3D, Mitsubishi Electric, 60 Hz) with a resolution of 1920 × 1080. A black frame was attached to the display to hide its frame. The position of the observer’s head was fixed with a chin and forehead rests at the position where the center of the eyes was toward the display center. The stimulus was observed in the upright state, which meant that the direction of the body coincided with the direction of physical gravity (Table 1). The participants used a numeric keypad to give their responses. The experiments were conducted in a dark room so that objects other than the stimulus were not observed.

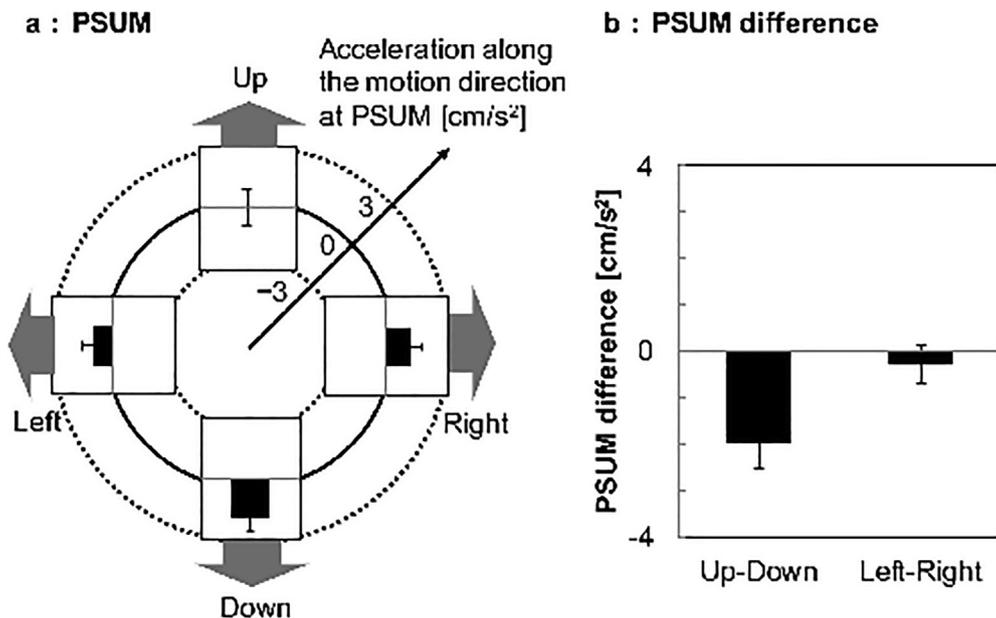
**2.1.4. Procedure**

The circle stimulus started moving when the participant pressed a key. After observing the stimulus, he or she was given a two-alternative forced choice about whether the moving stimulus appeared to have a positive or negative acceleration. The acceleration of the next trial was determined according to the response. For each motion direction condition, four staircase sequences beginning at ± 6 cm/s<sup>2</sup> of acceleration were conducted. One staircase terminated after 6 reversals of the response sequence. The participants were free to take a break between trials.

We used the maximum likelihood method to obtain a psychometric function plotting the ratio of positive/negative acceleration response as a function of physical acceleration and defined the acceleration where the response ratio was 0.5 as the PSUM.

**2.2. Results**

Fig. 1a shows the averaged acceleration of the PSUMs across nine observers. Each bar graph shows the result of each direction of stimulus motion (Right, Up, Left, and Down) with reference to the body and gravity axes. For example, the lower bar graph shows the result of the object moving downward on the display. In this paper, the motion direction is expressed with reference to the observer’s body axis. The radial axis shows the acceleration of perceptual uniform motion. The positive values (outward direction) indicate that the motion at PSUM is



**Fig. 1.** Averaged acceleration in perceptual uniform motion on frontal parallel plane with No-background across nine observers. (a) Bar graph of PSUM in each motion direction. Each bar graph shows the result of each direction of stimulus motion (Right, Up, Left, and Down). The radial axis along the motion direction in each figure shows the acceleration [cm/s<sup>2</sup>] at the point of subjective uniform motion (PSUM). The positive sign (outward direction) indicates that the motion at PSUM is physically accelerated, whereas the negative sign (inward direction) indicates that the motion at PSUM is physically decelerated. The error-bars show the standard error of the means. (b) PSUM difference among paired motion directions. The vertical axis shows the PSUM difference among paired motion directions, and the horizontal axis shows the set of motion directions. The error-bars show the standard error of the means.

physically accelerated, and negative values (inward direction) indicate that the motion at PSUM is physically decelerated. The unit of the acceleration value is  $\text{cm/s}^2$ . The vertical axis in Fig. 1b shows the PSUM difference among paired motion directions, and the horizontal axis shows the set of motion directions.

The results showed that the acceleration contained in the subjective uniform motion in the horizontal directions is different from zero and there is no difference between rightward and leftward motions. The acceleration contained in the subjective uniform motion in the vertical directions shows apparent anisotropy. For the upward direction of motion, the acceleration was almost zero, but for the downward direction of motion, the acceleration was much larger. One sample t-tests, which is the physical constant velocity, showed a significant difference only in the downward motion (Up  $t(8) = -0.024$ ,  $p = 0.98$ , Down  $t(8) = -3.61$ ,  $p < 0.01$ , Left  $t(8) = -1.50$ ,  $p = 0.17$ , Right  $t(8) = -2.12$ ,  $p = 0.067$ ). A one-way ANOVA with the motion direction (Up, Down, Left, Right) showed a significant main effect of motion direction ( $F(3,24) = 6.15$ ,  $p < 0.01$   $\eta^2 = 0.12$   $\omega^2 = 0.091$ ). Multiple comparison tests using Ryan's method ( $\alpha = 0.05$ ) showed that the difference between upward and downward motion was significant ( $t(24) = 4.25$ ,  $p < 0.05$ ) (see Table S1 for details). These results suggesting that the PSUM on the frontal parallel plane is affected by the gravity direction.

### 3. Experiment 2

We investigated the effect of the visual polarity on the PSUM of an object moving on the frontal parallel plane. As in Experiment 1, we measured the acceleration (acceleration bias) of subjective constant velocity in the visual polarity (landscape photo), in up, down, left, or right motion directions on the frontal parallel plane. We also manipulated the up-down direction in the visual polarity of the background (Fig. 2). When the up-down direction of the background coincided with the direction of gravity direction, we expected that the acceleration bias in the vertical motion (negative acceleration for upward motion and positive acceleration for downward motion) would increase for the perception of constant velocity shown in Experiment 1. On the other hand, we expected that when the up-down direction in the visual polarity was opposite to that of gravity direction, acceleration bias would decrease.

#### 3.1. Materials and methods

##### 3.1.1. Participants

The apparatus and observers (nine) were the same as in Experiment 1.

##### 3.1.2. Visual stimulus and procedure

The motion stimulus was the same as in Experiment 1. The background stimulus was one of four color images ( $1080 \times 1080$  pixels), as shown in Fig. 2 (left column). The average luminance of the background images was 58.0 (Ground), 51.4 (Room), 78.5 (Building) or  $47.6 \text{ cd/m}^2$  (Hole). Each image was presented correlating with an upright (Normal) or upside down (Inversion) direction relative to the body direction. Table 1 shows the relationship among body axis, environmental gravity, visual polarity, and motion direction. Other aspects of visual stimulus were the same as those in Experiment 1.

Each session contained one of the background images and the procedure was the same as in Experiment 1. The order of background conditions was randomized for each observer.

#### 3.2. Results

One observer was excluded as an outlier because the data was outside the range of  $\pm 2SD$  from the mean in almost all conditions. Fig. 2 shows the averaged PSUMs and PSUM difference in the Normal

and Inversion background conditions across eight observers for each background type. Fig. 2a–d show the difference in background conditions of Ground, Room, Building and Hole, respectively. As in Fig. 1, the circular figure includes for panels of bar graph to show PSUM in each motion directions, and the right figure is a bar graph of PSUM difference between paired motion directions. In both the graphs, the symbol color indicates the direction of the visual background: Normal (black) and Inversion (gray).

As Fig. 2 shows, the motion direction seems to affect the perception of uniform motion, as in Experiment 1. The acceleration for subjective constant velocity appears smaller in the upward motion than in the other directions (leftward, rightward, and downward). However, this bias was mostly the same between the Normal and Inversion backgrounds, which was inconsistent with our prediction. In addition, there were no systematic differences observed in the results for the different backgrounds.

A two-way ANOVA with visual polarity (Normal, Inversion) and motion direction for each background type (Up, Down, Left and Right) showed a significant main effect of the motion directions in all background types (Ground ( $F(3,21) = 7.06$ ,  $p < 0.01$   $\eta^2 = 0.089$   $\omega^2 = 0.070$ ), Room ( $F(3,21) = 10.57$ ,  $p < 0.01$   $\eta^2 = 0.18$   $\omega^2 = 0.15$ ), Building ( $F(3,21) = 4.68$ ,  $p < 0.05$   $\eta^2 = 0.16$   $\omega^2 = 0.12$ ), and Hole ( $F(3,21) = 4.52$ ,  $p < 0.05$   $\eta^2 = 0.093$   $\omega^2 = 0.066$ )). The interaction was significant for Room condition only ( $F(3,21) = 4.03$ ,  $p < 0.05$   $\eta^2 = 0.038$   $\omega^2 = 0.027$ ). Multiple comparison tests using Ryan's method ( $\alpha = 0.05$ ) showed that the difference between upward and downward motion was significant in all background types ( $p < 0.05$ ) (see Table S1 for details). These results suggest that the PSUM is affected by the gravity and body directions as in Experimental 1. We infer that the effect of visual polarity is very weak or none in this experiment because the effect was seen only in the Room condition.

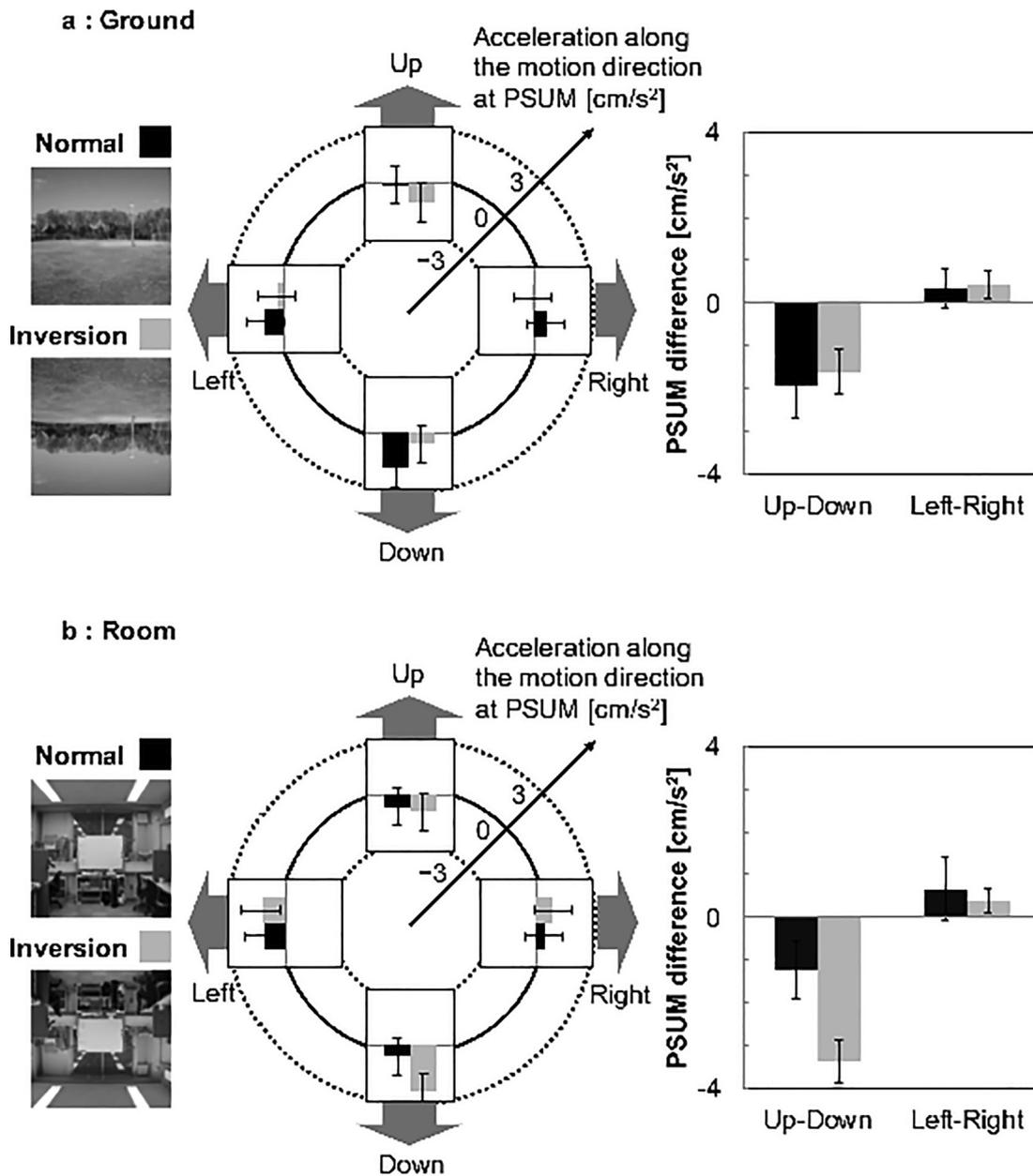
To consider the interpretation that the visual background added noise to the visual motion estimate, we calculated the just noticeable difference (JND) of the acceleration bias from the psychometric functions in each condition and compared it to the results from Experiment 1 for all observers. The JND was defined as a difference between the acceleration values at 75% and 25% points of the psychometric function. Fig. 3 shows the JND ratio of the condition With-background (Experiment 2) to that with No-background (Experiment 1). The ratios were greater than 1, except for the condition of "Ground", meaning that the participants had high JND to the acceleration change when presented with background image in most cases (Experiment 2). We assume that small local objects or high spatial frequencies in the background photos may affect the PSUM, resulting in differences by background types, rather than the background photos providing the up-down direction information.

The experiment did not reveal any effect of visual polarity. This could be because up-down direction cue from the gravity direction would be stronger than visual polarity. We consider that the visual polarity effect could be observed if the body axis and the gravity direction are dissociated. In Experiment 3, the participants laid on their backs or on one side to separate the gravity direction from the body axis to test this assumption.

### 4. Experiment 3

The results of Experiment 2 showed that the up-down direction in the visual polarity did not affect two-dimensional PSUM. However, it is too early to conclude that there was no effect of visual polarity (the up-down direction) because in Experiment 2, the gravity direction corresponded to the direction of the body axis.

In Experiment 3, we investigated the effect of visual polarity on perceived acceleration, changing the relationship among visual polarity, the gravity direction, and body direction by manipulating the posture of the observer. If PSUM is affected by the up-down direction based on the three sources of information, we assumed that the relative



**Fig. 2.** Averaged acceleration in perceptual constant velocity of motion on frontal parallel plane with a background of natural scene across eight observers for each condition of background (a-d), which is shown at the left side of each set of pictures and panels. There was a Normal background, in which the physical gravity direction is consistent with the visual polarity in the photograph, and an Inversion background, in which the image was inverted upside-down. The middle circular graph is the results of PSUM for each motion direction. Each bar graph shows the result of each direction of stimulus motion (Right, Up, Left, and Down). The right panel is a bar graph of PSUM difference between paired motion directions. In both the graphs, the black and gray bars represent the background conditions (Normal and Inversion), and the other format of the figure is identical to Fig. 1a.

contribution of visual polarity increased when the body direction and the gravity direction were separated.

#### 4.1. Materials and methods

##### 4.1.1. Participants

Seven of the participants from Experiments 1 and 2 took part in Experiment 3 (1 female, mean age = 28.4 (25–30) years).

##### 4.1.2. Visual stimulus

The motion stimulus was the same as in Experiment 1 and 2. One of the background stimuli, “Ground”, used in Experiment 2 (Stimulus Ground in Fig. 2) was employed here because it had the same JND to acceleration bias as the No-background condition (Fig. 3). The direction

of the background stimulus was either Normal, Inversion, rotated clockwise by 90° (CW90°), or rotated counterclockwise by 90° (CCW90°) relative to the body axis. There was also a condition with no (gray) background. Other aspects of visual stimulus were the same as those in Experiment 1 and 2.

##### 4.1.3. Posture condition

There were two posture conditions: Supine and Lateral. In the Supine condition (Fig. 4a, Experiment 3a), the participant laid on his or her back so that the body direction and gravity direction were orthogonal, as were the motion direction and gravity direction. In the Lateral condition (Fig. 4b, Experiment 3b), the participant laid on his or her left side so that the body direction and gravity direction were orthogonal and the angles between the motion direction and gravity direction were

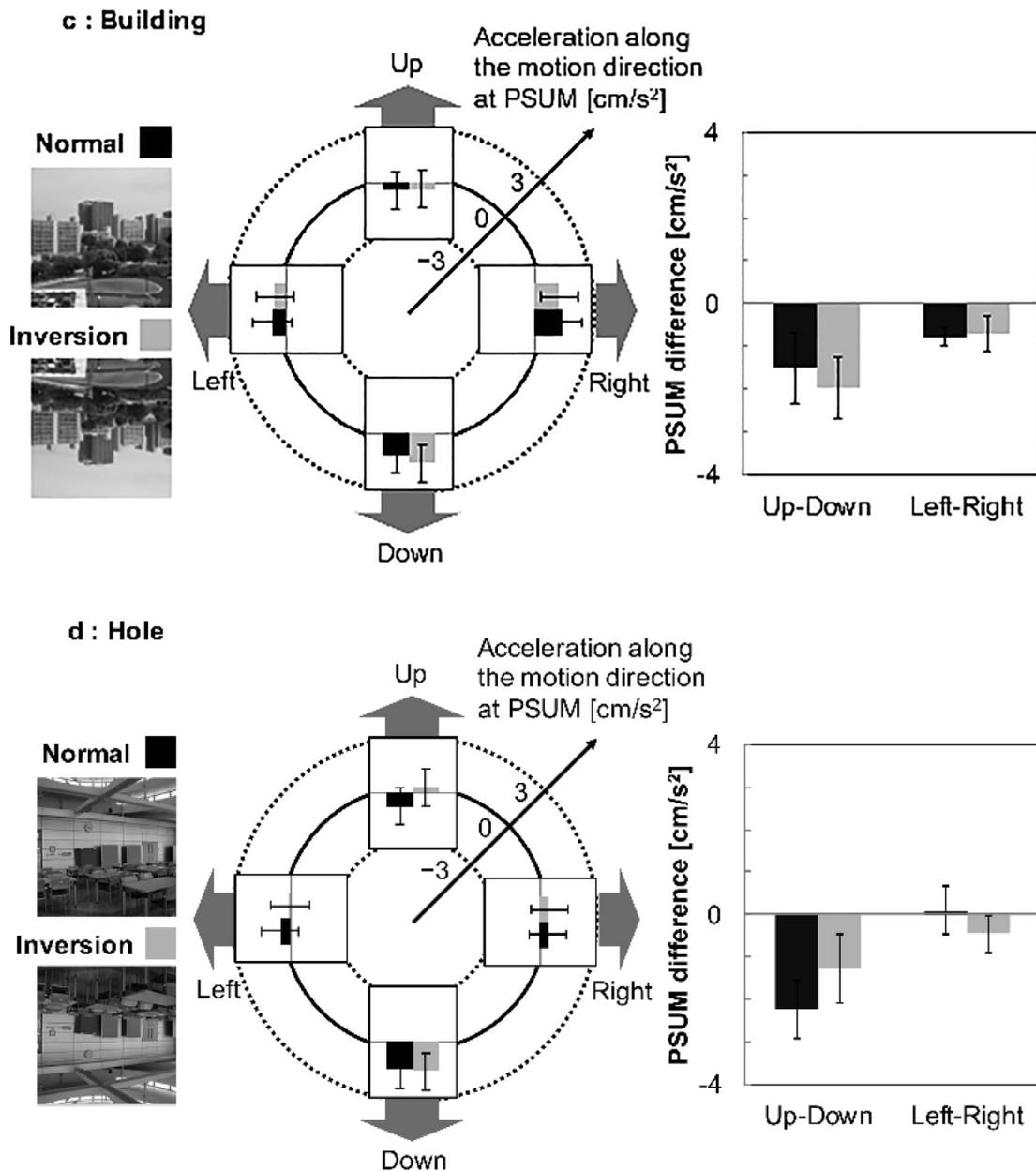


Fig. 2. (continued)

0, 90, 180, or 270° on the frontal parallel plane to observer.

4.1.4. Apparatus

All the apparatuses were basically the same as in Experiment 1 and 2 except for the equipments to fix positions of display and observer's posture. The display was fixed above the participant in the supine condition and beside the bed in the lateral condition, as shown in Fig. 5. The viewing distance was 38 cm and the participant's head position was adjusted to be the same relative to the position of the display, as in Experiments 1 and 2.

4.2. Results for the Supine condition (Experiment 3a)

Fig. 5 shows the averaged acceleration contained in the motion with subjective constant velocity across all seven participants in each background condition in the Supine condition.

In the No-background condition (Fig. 5b), like in Experiment 1, the acceleration bias for the motion with subjective constant velocities in horizontal directions seemed the same, and those in the vertical

directions were different. A one-way ANOVA with the motion direction (Up, Down, Left, Right) showed a significant main effect of motion direction ( $F(3,18) = 8.11, p < 0.01, \eta^2 = 0.21, \omega^2 = 0.17$ ). Multiple comparison tests using Ryan's method ( $\alpha = 0.05$ ) showed significant differences between the results for the upward and downward ( $t(18) = 4.55, p < 0.01$ ), upward and leftward ( $t(18) = 3.50, p < 0.01$ ), and upward and rightward ( $t(18) = 3.73, p < 0.01$ ) motion conditions (see Table S1 for details).

The results for the Normal and Inversion conditions (Fig. 5c) are consistent with those of the No-background condition. However, acceleration bias for the motion with the subjective constant velocity increased positively in the upward direction and increased negatively in the downward direction in the Inversion condition than in the Normal condition. A two-way ANOVA with the visual polarity (Normal, Inversion) and the motion direction (Up, Down, Left, Right) showed a significant main effect of motion direction ( $F(3,18) = 8.11, p = 0.13, \eta^2 = 0.19, \omega^2 = 0.16$ ) and interaction ( $F(3,18) = 4.19, p < 0.05, \eta^2 = 0.038, \omega^2 = 0.027$ ). Multiple comparison tests using Ryan's method ( $\alpha = 0.05$ ) showed that the differences between the results in

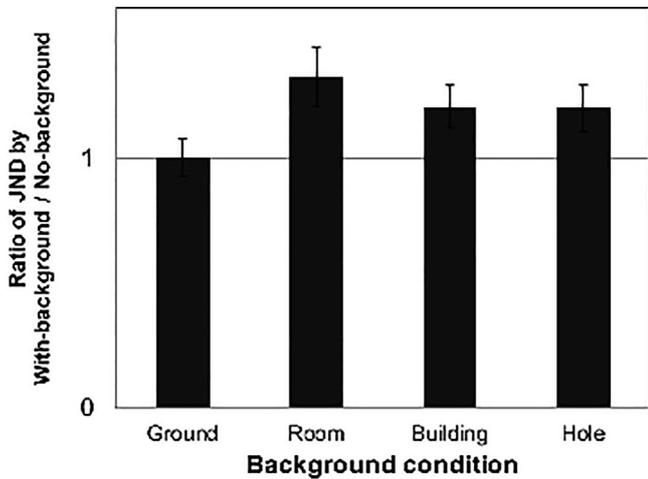


Fig. 3. JND ratio of the No-background and With-background conditions. The horizontal axis indicates the background condition, each of them is corresponding to image shown in Fig. 2. The vertical axis is the JND ratio obtained by dividing the JND measured for each background in Experiment 2 by the JND measured in Experiment 1 for each participant. This ratio was calculated and averaged across all motion directions. The error-bars show the standard error of the means.

the upward and downward ( $t = 5.78$   $df = 36$ ,  $p < 0.01$ ), upward and leftward ( $t(36) = 3.24$ ,  $p < 0.01$ ), upward and rightward ( $t(36) = 2.41$ ,  $p < 0.05$ ), downward and leftward ( $t(36) = 2.55$ ,  $p < 0.05$ ), and downward and rightward ( $t(36) = 3.37$ ,  $p < 0.01$ ) motion directions in the Normal condition were significant (see Table S2 for details). These results indicate that the effect of visual polarity on the PSUM becomes greater when the body direction is different from gravity direction.

The results of the CCW90° and CW90° background conditions (Fig. 5d) show that acceleration bias for the motion with subjective constant velocity was larger when the motion direction was the same as the visual polarity compared to when the directions were opposite to each other. For example, in the case of rightward motion, the acceleration bias was larger for the CW90° condition than for the CCW90° condition. A two-way ANOVA with the visual polarity (CCW90°, CW90°) and motion direction (Up, Down, Left, Right) showed a significant main effect of motion direction ( $F(3,18) = 14.93$ ,  $p < 0.01$   $\eta^2 = 0.30$   $\omega^2 = 0.26$ ) and interaction ( $F(3,18) = 3.88$ ,  $p < 0.05$   $\eta^2 = 0.039$   $\omega^2 = 0.027$ ). Multiple comparison tests using Ryan’s method ( $\alpha = 0.05$ ) showed that the differences between the results in the upward and downward ( $t(36) = 4.96$ ,  $p < 0.01$ ), upward and leftward ( $t(36) = 3.43$ ,  $p < 0.01$ ), and upward and rightward ( $t(36) = 4.45$ ,  $p < 0.01$ ) motion direction in CCW90° were significant (see Table S2 for details). The differences between the results in the upward and downward ( $t(36) = 5.11$ ,  $p < 0.01$ ), upward and leftward ( $t(36) = 5.32$ ,  $p < 0.01$ ), upward and rightward ( $t(36) = 2.43$ ,  $p < 0.05$ ), downward and rightward ( $t(36) = 2.67$ ,  $p < 0.05$ ), and leftward and rightward ( $t(36) = 2.89$ ,  $p < 0.01$ ) motion direction in CW90° were also significant (see Table S2 for details). We found that when the body direction was inconsistent with gravity direction, the up-down direction in the visual polarity affected the PSUM of motion along the direction.

4.3. Results for the Lateral condition (Experiment 3b)

Fig. 6 shows the averaged acceleration contained in the motion with subjective constant velocities across all seven observers in each background condition in the Lateral condition.

In the No-background condition (Fig. 6b), there was no difference in the acceleration bias between the horizontal directions of motion on the display, although the direction of environmental gravity was consistent

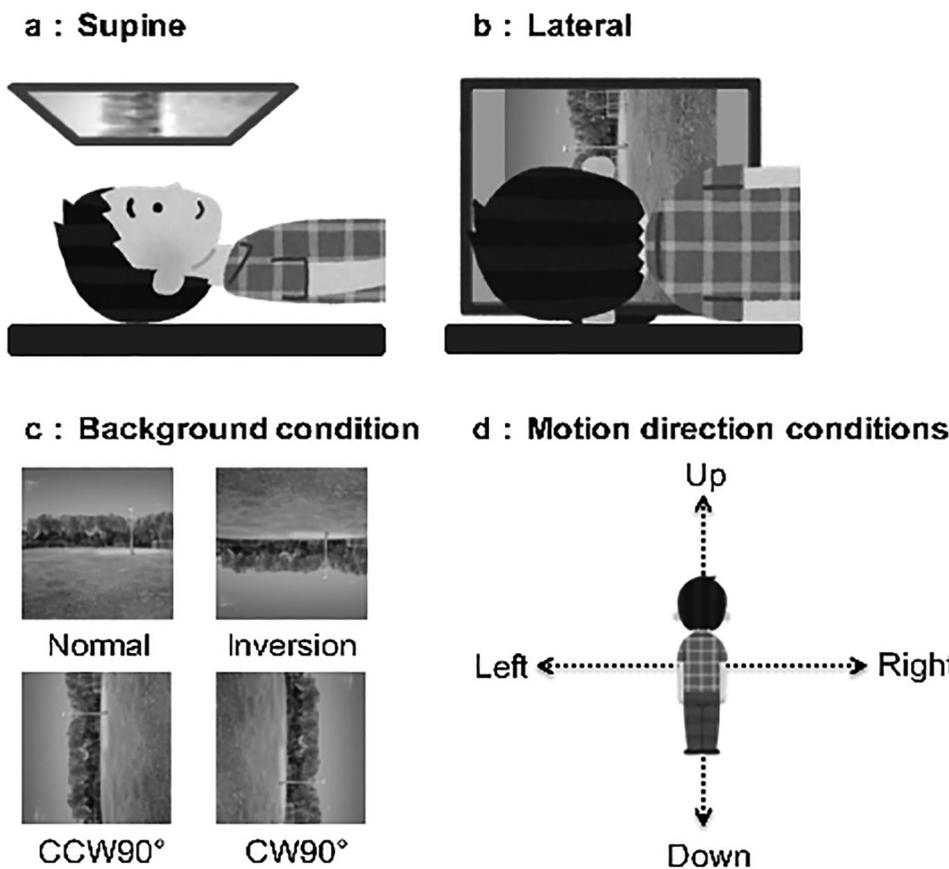
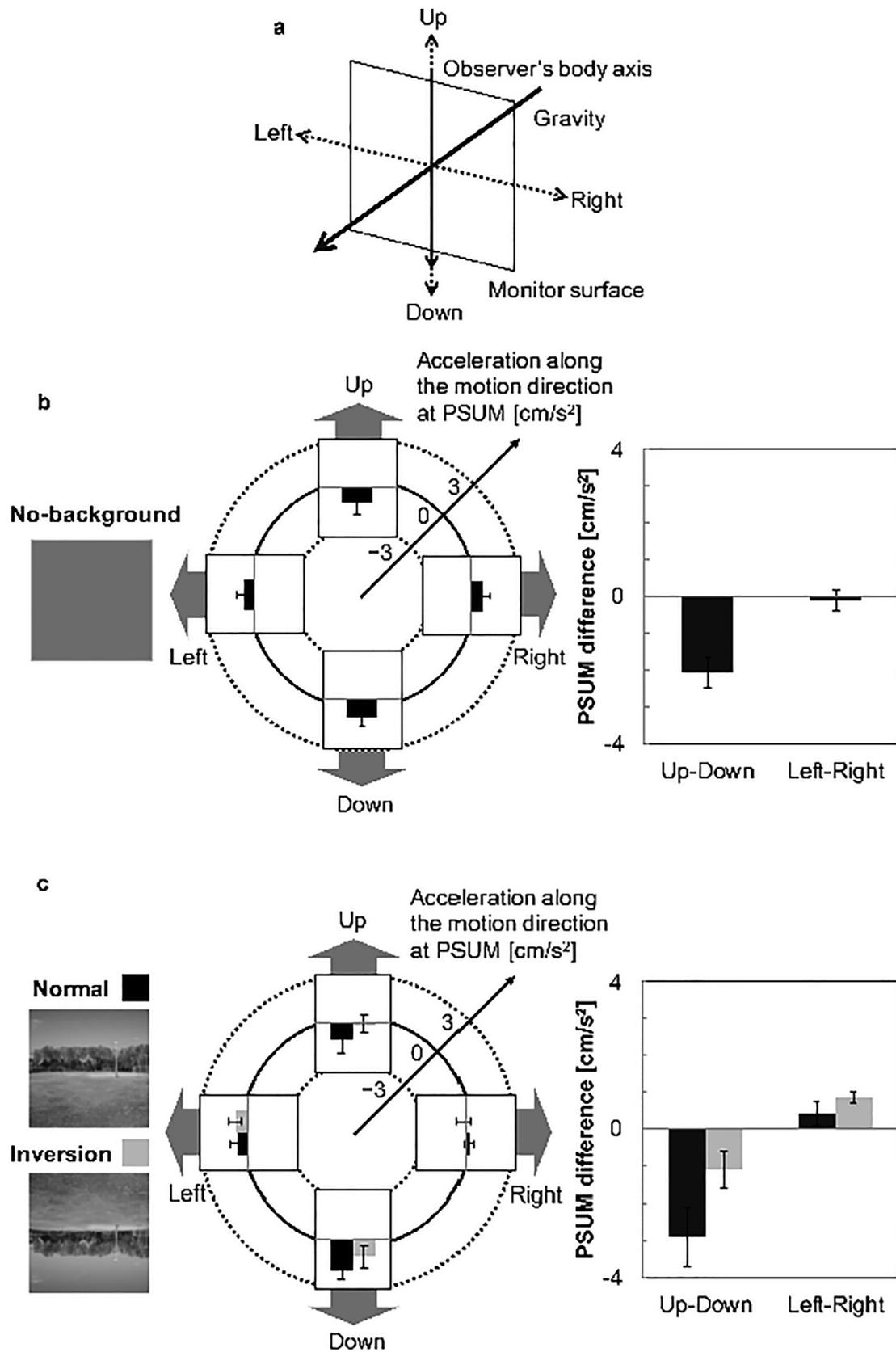


Fig. 4. Relationship among the directions of body, visual stimulus, and gravity in Experiment 3. (a) Supine condition. (b) Lateral condition. Both figures show the positional relationship between the display and the participant. (c) The visual background conditions. (d) The directions of stimulus motion (Right, Up, Left, and Down). The directions of visual background and stimulus motion were defined relative to the body axis of the participant.



**Fig. 5.** Averaged acceleration in perceptual constant velocity of motion on the frontal parallel plane in the Supine condition for visual stimulus, with (b) No-background, (c) Normal and Inversion, and (d) CCW90° and CW90° across seven observers. The pictures in the left column show the background stimuli. The middle column is the results of PSUM for each motion directions. Each bar graph shows the result of each direction of stimulus motion (Right, Up, Left, and Down). The right column is a bar graph of PSUM difference between paired motion directions. In both the graphs, the black and gray bars represent the background conditions (Normal and Inversion or CW90° and CCW90°) and the other format of the figure is identical to Fig. 1a. (a) shows the relationship of the directions of gravity, body, and motion in the Supine condition.

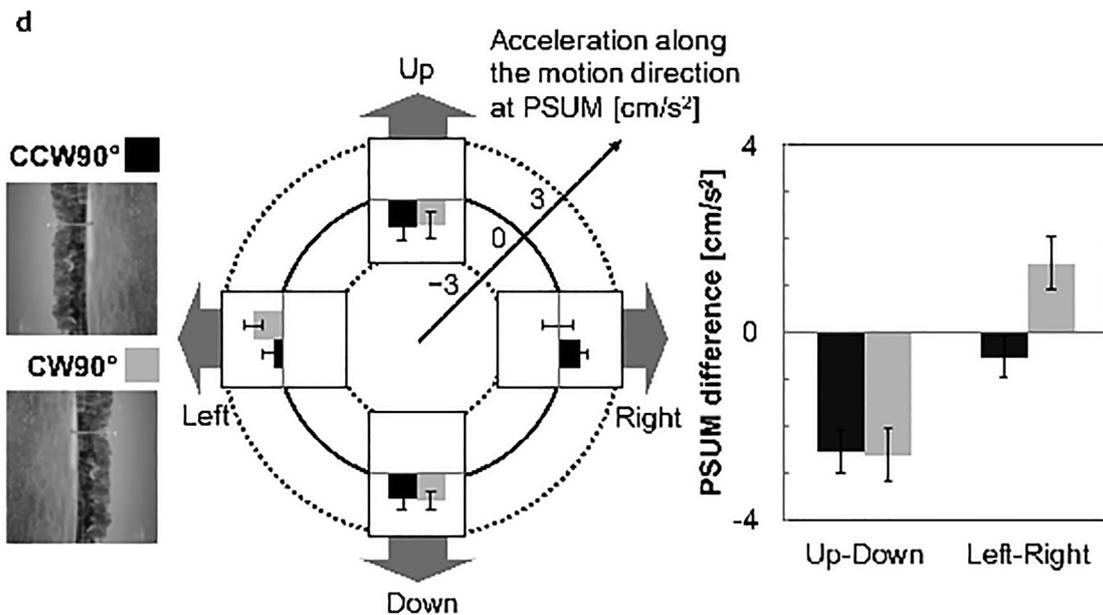


Fig. 5. (continued)

with the leftward motion and inconsistent with the rightward motion. On the other hand, there was a difference of acceleration bias in the vertical direction, as was also the case in Experiments 1, 2, and 3a. In this instance, the downward motion being consistent with the downward direction of the participant's body showed a larger bias of acceleration. A one-way ANOVA with the motion direction (Up, Down, Left, Right) showed a significant main effect of motion direction ( $F(3,18) = 7.43$ ,  $p < 0.01$ ,  $\eta^2 = 0.23$ ,  $\omega^2 = 0.18$ ). Multiple comparison tests using Ryan's method ( $\alpha = 0.05$ ) showed that the differences between the biases in upward motion and other motion directions (downward ( $t(18) = 4.14$ ,  $p < 0.01$ ), and that in leftward ( $t(18) = 3.85$ ,  $p < 0.01$ ) and rightward motion ( $t(18) = 3.44$ ,  $p < 0.01$ )) were significant (see Table S1 for details).

The results for the Normal and Inversion conditions (Fig. 6c) were basically consistent with the results in Fig. 5c. Downward motion showed a larger bias of acceleration. Regarding the difference in the results of Normal and Inversion conditions, the acceleration bias in the downward motion direction decreased in the Inversion background. There was no difference in the Normal and Inversion background conditions for the motion of horizontal directions. A two-way ANOVA with visual polarity (Normal, Inversion) and motion direction (Up, Down, Left, Right) showed a significant main effect of the motion directions ( $F(3,18) = 5.41$ ,  $p < 0.01$ ,  $\eta^2 = 0.16$ ,  $\omega^2 = 0.12$ ). Multiple comparison tests using Ryan's method ( $\alpha = 0.05$ ) showed the difference between upward and downward directions ( $t(18) = 4.00$ ,  $p < 0.01$ ) was significant (see Table S1 for details).

The results in CCW90° and CW90° background conditions (Fig. 6d) show that the acceleration bias in motion with subjective constant velocities was larger when the motion direction was the same as the gravity direction from the visual polarity (rightward in CCW90° and leftward in CW90°) than the opposite case (rightward in CW90° and leftward in CCW90°). Regarding the motion of vertical directions in the results of the CCW90° and CW90° conditions, the acceleration bias was consistently larger in the downward direction than in the upward direction. A two-way ANOVA with visual polarity (CCW90°, CW90°) and motion direction (up, down, left, right) showed a significant main effect of motion direction ( $F(3,18) = 4.03$ ,  $p < 0.05$ ,  $\eta^2 = 0.18$ ,  $\omega^2 = 0.13$ ), and interaction ( $F(3,18) = 4.26$ ,  $p < 0.05$ ,  $\eta^2 = 0.071$ ,  $\omega^2 = 0.52$ ). Multiple comparison tests using Ryan's method ( $\alpha = 0.05$ ) showed that the differences between the results in the upward and rightward ( $t(36) = 3.31$ ,  $p < 0.01$ ) motion direction in the CCW90° condition, and

those between the results in the upward and leftward ( $t(36) = 3.51$ ,  $p < 0.01$ ) for motion direction in the CW90° condition were significant (see Table S2 for details). As with supine posture, we found contrasting change in the acceleration bias of motion with subjective constant velocities along the up-down direction in the visual polarity. These results suggest that the PSUMs on the frontal parallel plane are affected by the visual polarity parallel with the up-down directions of the body or gravity axes when the body axis and gravity axis are separated.

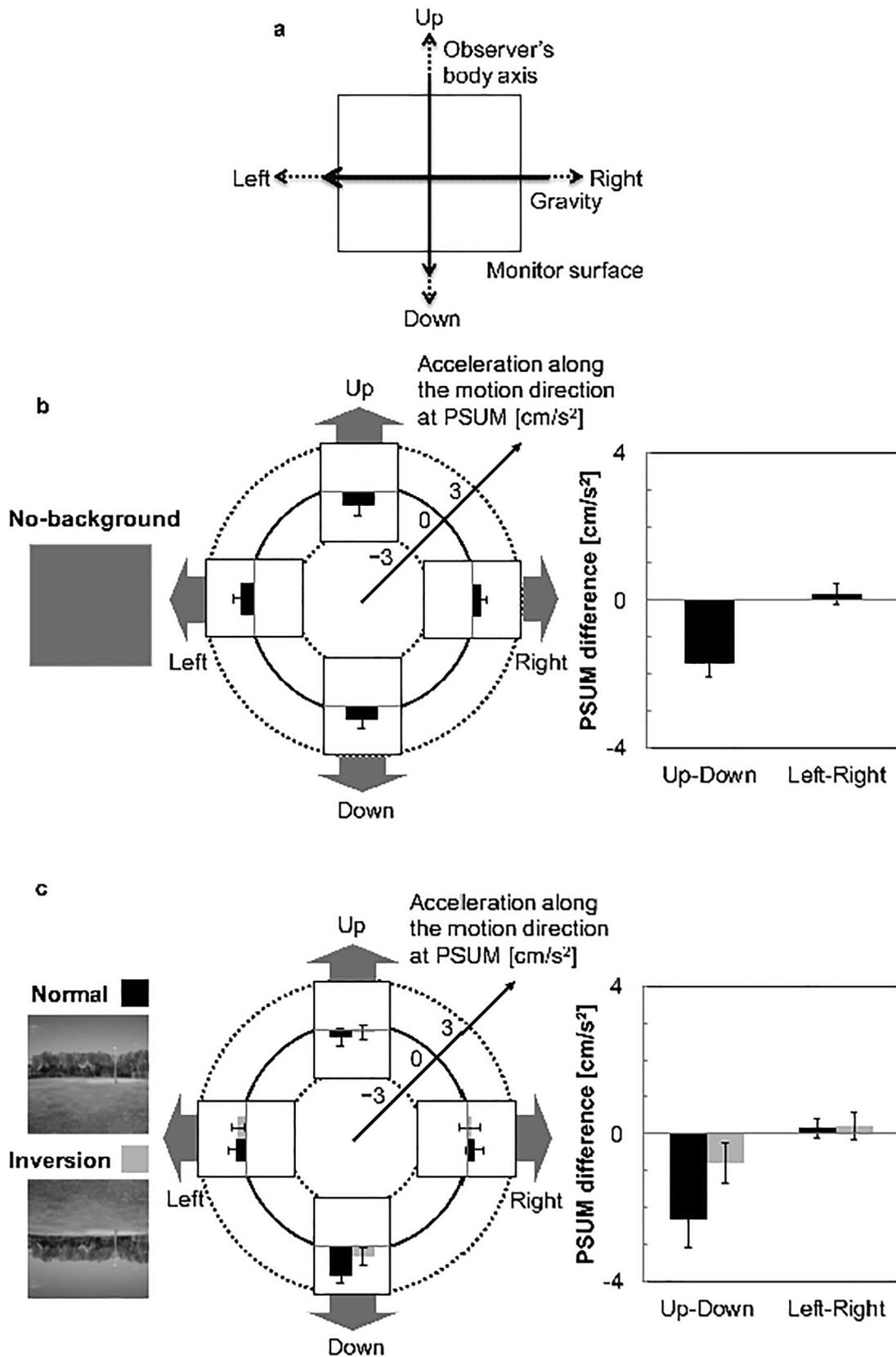
## 5. Discussion

In this study, we examined whether motion direction and up-down direction perception from several cues affected perceived uniform motion. Experiment 1 showed that the acceleration bias for subjective uniform motion changed depending on the motion direction, which is consistent with the previous study (Asano et al., 2008). In the case of upward motion, the acceleration at PSUM shifted toward negative (reduction of velocity), and in the case of downward motion the shift was the opposite.

In Experiment 2, we examined whether a visual polarity that provided up-down direction affected the PSUMs. The effect of the visual polarity was not seen in any conditions. However, the results showed acceleration bias along the vertical motion direction as in Experiment 1. We considered that this was because the gravity and body directions (and the consistency of them) were too strong for the cognitive system to consider the visual polarity.

In Experiment 3, the participants laid in supine or lateral positions to separate the body direction from the physical gravity direction. In this case, the acceleration bias in PSUMs in the Inverted-background condition decreased compared with that in the Normal-background condition (Fig. 5b and 6b). In addition, there was a significant difference between the results for the CCW90 and CW90 conditions (Fig. 5c and 6c).

We considered that the acceleration bias observed in the present experiments was produced because of the adaptation to motion under gravity. The "adaptation" here indicates the perceptual modification in general due to the visual stimulation in daily life. It occurred at any processing stage of visual system, not only at the low level stage. The direction of acceleration bias shown in Experiment 1 matched the natural motion under gravity in daily life, in which an object moving downward accelerates and one moving upward decelerates, but an



**Fig. 6.** Averaged acceleration in perceptual constant velocity of motion on the frontal parallel plane in the Lateral condition for the visual stimulus of (b) No-background, (c) Normal and Inversion, and (d) CCW90° and CW90° across seven observers. The pictures in the left column show the background stimuli. The middle column is the results of PSUM for each motion direction. Each bar graph shows the result of each direction of stimulus motion (Right, Up, Left, and Down). The right column is a bar graph showing the PSUM difference among paired motion directions. In both the graphs, the format of the figure identical to Fig. 5(a) shows the relationship of the directions of gravity, body, and motion in the Lateral condition.

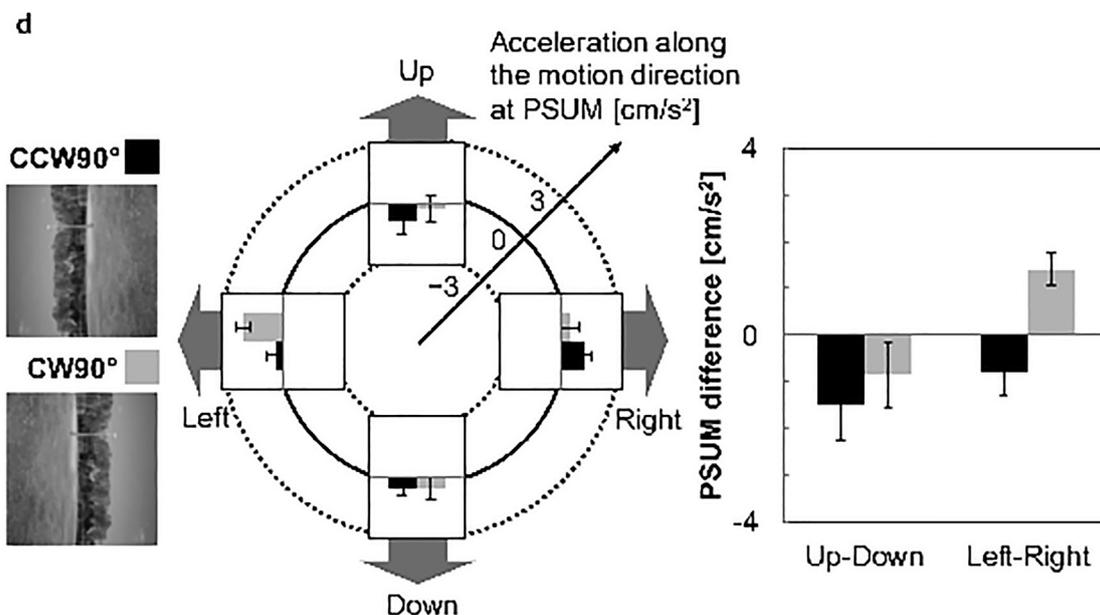


Fig. 6. (continued)

object moving left- or rightward moves with a constant velocity (or a little deceleration due to air resistance). The magnitude of acceleration bias was much smaller than that of gravitational acceleration ( $9.8 \text{ m/s}^2$ ). The results of our Experiment 1 indicate that subjective uniform motion adapts to gravitational acceleration. As with perceptual adaptation, such as color and motion aftereffects, humans adapt to visual properties when they are exposed to a certain stimulus or situation for a long time. We cannot normally observe the movement of an object outside the gravity environment, so we adapt to gravity's acceleration and increase our sensitivity to motion acceleration that is not due to gravity. Furthermore, this acceleration bias (it would be the result of adaptation to gravity acceleration) occurs along the axis of the body or is represented on retinal coordinates here, indicating that this adaptation occurs at multiple stages in visual processing.

Then, what kind of up-down direction cues would contribute to our perception of acceleration? The results in our Experiment 3 show that not only gravity direction, but also visual polarity seems to contribute to the perception of motion. In Experiment 3, the visual polarity of the background affected the shift of PSUMs. The difference of PSUMs between the upward and downward conditions was larger than that between the Normal background and Inversion conditions and the bias occurred with left- and rightward motion when the background was rotated by  $90^\circ$  (CW90 and CCW90 conditions). Visual polarity provides the positional and structural information in space and indicates the direction of gravity. For example, the sky and ground, the direction of trees and buildings, and the position of illumination provide natural clues about gravity.

Moreover, the orientation of the longitudinal body axis was also shown to cause PSUM acceleration bias. In the No-background condition of Experiment 3a, it is impossible to obtain direction information visually. And the direction of physical gravity is orthogonal to the frontal parallel plane. Nevertheless, acceleration bias was observed between Up and Down motions. Therefore, it is suggested that the "down" direction indicated by the longitudinal body axis (Mittelstaedt, 1998) affects the acceleration bias in motion perception. However, we cannot conclude which coordinate system is related to the acceleration bias along the body's axis observed in the present experiment: body-centered, head-centered, or retinotopic coordinates. Previous study has suggested that subjective visual vertical accesses gravity perception based on the head-centered coordinate system (Fraser, Makooie, & Harris, 2015). Therefore, probably head-centered or retinotopic

coordinates are related to acceleration bias.

The results of Experiment 2 were not significant for background conditions other than Room condition. In the Room condition, bias showed the opposite direction to visual polarity in Inversion. We consider these results to mean that there was no effect of the visual polarity on the shift of PSUMs in this experiment. We proposed that this was because the up-down direction cue from both gravity direction and body direction was so strong that the effect of the visual polarity was inhibited. Many previous studies (e.g. Bringoux, Nougier, Marin, & Barraud, 2003, Mittelstaedt, 1997, Trousselard, Cian, Nougier, & Pla, 2003) showed that visual or cognitive factors, like visual polarity or perceptual gravity direction, strongly affect the perceived vertical axis when the body axis is not parallel to the direction of gravity. Some studies proposed a computational model of human perceptual process to integrate information from visual contents, the gravity and body directions to decide perceived "up" direction (Jenkin et al., 2004, Harris et al., 2014) as mentioned in Introduction, and the weighting factors would change with the posture. From the results in this study, we suppose that the relationship among motion direction and the up-down direction cue indicated by gravity direction and by body axis can increase or decrease the effect of visual polarity.

Results in the three experiments clearly showed that up-down cue from gravity direction, visual scene polarity, and longitudinal body axis affected PSUM, and we suppose that the "down" direction obtained from the integration of these three cues is responsible to decide the bias in motion perception. Regarding the way to integrate the three signals for the acceleration bias in motion perception, the vector integration model mentioned above (Jenkin et al., 2004, Harris et al., 2014) could explain the results. However, the "down" direction based on this model cannot explain all of the present results. There was no effect of visual polarity in Experiment 2. In the result of a condition with No-background in Experiment 3b, acceleration bias was observed in the motion direction parallel with longitudinal body axis, but no bias was observed in the motion direction parallel with the gravity direction. If the integrated directional signal always affects motion perception, some bias should be seen in those conditions. The sensory integration model of robust estimation in which some cues are discarded if there is a large conflict between the cues (Landy, Maloney, Johnston, & Young, 1995, Knill, 2007) could also explain the present results. This model is consistent with the present results because a visual cue with a large conflict with other cues seemed to be discarded in Experiment 2, and gravity

**Table 2**  
Summary of the results in Experiments 1, 2, and 3.

Experiment	Experimental condition	Downward direction			Motion direction	Observed of acceleration bias
		Body direction	The gravity	Visual polarity		
Exp1		↓	↓	—	↕	Yes
					↔	No
Exp2		↓	↓	↕	↕	Yes
					↔	No
Exp3a		↓	⊙	↕	↕	Yes
					↔	No
					↕	Yes
					↔	Yes
Exp3b		↓	←	↕	↕	No
					↔	Yes
					↔	Yes

Each column, from left to right, shows the experiment number, experimental setup, body direction, physical gravity direction, up-down direction in the visual background, condition of motion direction, and acceleration bias observed in the experiment, respectively.

direction cue with a large conflict to the longitudinal body axis seemed to be discarded in Experiment 3b. Additionally, it is important and interesting to investigate whether the perceptual down direction used for motion bias and that used for other perception are similar. In the future, it will be necessary to increase the condition of motion direction and to measure several perceptual responses at the same time to answer the question.

## 6. Conclusions

Table 2 summarizes the study results. Experiment 1 showed that the physical gravity direction affects the PSUM of an object moving on the frontal parallel plane. Then, Experiment 3 revealed that up-down direction in the visual polarity affects the PSUM when the body direction and physical gravity direction are inconsistent. However, Experiment 2 showed that visual information does not affect the PSUM when the directions of body and physical gravity are consistent. Together, these results indicate that the up-down direction ascertained from different sources of information affects PSUM and the combination of up-down direction information from different cues is important for the effects. The output of the integration process could be based on a linear summation of the signals using the reliability of the signal as the weight (Jenkin et al., 2004, Harris et al., 2014), or a non-linear summation according to, for example, the number of votes from several cues. In any event, we do not know fully understand the properties of the integration process of the gravity direction, visual polarity, and body direction at this point, and further consideration will be needed to comprehend the properties of sensory integration process and to predict the acceleration bias in PSUM with any combination of body direction, the visual polarity, and physical gravity in the environment.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.visres.2019.08.005>.

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